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HIGH TEMPERATURE HYDRAULIC SYSTEM ACTUATOR SEALS FOR USE IN ADVANCED SUPERSONIC AIRCRAFT

by

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ABSTRACT

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This report covers the first six-month period of a program to investigate seal materials and to design seals for high temperature hydraulic actuator application. In pursuing these objectives, work has progressed in the areas of test fixture design and fabrication, materials selection, materials evaluation, seal design, and preliminary seal testing.

Results of the initial fluid-material compatibility tests conducted with the F-50, MCS-3101, MCS-293, MLO-60-294, and PR-143AB fluids were inconclusive because of cross contamination of fluids between test manifolds.

Five rod seal designs are currently being developed. The seal configuration fabricated of a polyimide (Polymer SP) plastic has been evaluated at 400°F, 500°F, and 600°F, with promising results.

Author

HIGH TEMPERATURE HYDRAULIC SYSTEM
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SUMMARY

This report describes activities during the first six-month period of NASA Contract NAS 3-7264, ending 30 September 1965. In accordance with program objectives, progress was made in the following areas:

(1) Preparation of existing test equipment and design and fabrication of new fixtures and apparatus

(2) Selection and procurement of candidate seal materials and fluids

(3) Fluid compatibility testing of materials initially selected

(4) Seal design and preliminary evaluation of candidate seal configurations.

As of the end of the reporting period, the existing cycling rig for preliminary seal evaluation has been placed in operation. Test fixtures for investigating seal loading and wear characteristics of materials are being fabricated. Fabrication of the test rig for the low pressure and endurance test phases is progressing. An initial run made with the fluid compatibility test apparatus indicated that minor modifications to the apparatus were required to prevent cross-contamination of fluids between manifolds.

Candidate seal materials were selected for further screening. The materials were selected on the basis of past performance and on known friction and wear characteristics. In general, the materials cover the range of plastics, ductile metals, and hard metals. The compatibility of these materials with candidate fluids is presently under study.

Design concepts for the low pressure rod seal are being developed. Preliminary testing of two rod seals fabricated of polyimide plastic has been conducted to determine friction, wear, and leakage characteristics. Results of this experimental work are very encouraging. The seal was operated successfully at 400°F and 500°F with no leakage. However, at the completion of the 600°F operation, leakage of 5 drops per minute occurred at one of the seals. Leakage was caused by the seal gland nut backing off, resulting in excessive axial clearance in the seal assembly.

INTRODUCTION

The concept of sustained supersonic flight has become a reality within the past several years and the trend for the future is toward the development of even higher speed aircraft. As operating conditions become more severe with succeeding families of vehicles, design margins will decrease substantially. Not the least to be affected by these considerations are hydraulic system components, particularly the dynamic seals. Elastomeric seals are now meeting the requirements of current aircraft operating in the temperature range of -65°F to +275°F. However, the temperature extremes anticipated for future air vehicles will impose severe demands on these materials and will limit their use.

Recent research programs on high temperature seals, conducted by the contractor and summarized in ASD-TDR-63-573 and ML-TDR-64-266, indicated that the maximum operating temperature permissible with present day elastomers is 400°F. However, polyimide plastics and certain silver base materials have shown promise of performing satisfactorily above 400°F. These latter materials are strongly considered for seal applications in this present program, which has as its objective the investigation of seal materials and the design of seals for potential use with hydraulic fluids in advanced supersonic aircraft. This investigation is directed to dynamic rod seals intended to function efficiently for 3000 hours in the temperature range of -40°F to +600°F, and operating pressures to 4000 psi.

Emphasis is placed on integrating material properties and seal design to obtain the optimum seal-material combination. The specific tasks to be accomplished are:

Task I	-	Preparation of existing test facilities and design and fabrication of seal test actuators and fixtures.
Task II	-	Selection, procurement and evaluation of candidate seal materials
Task III	-	Design of seals for the 1-inch and 3-inch rod sizes
Task IV	-	Low pressure testing of 1- and 3-inch rod seals at temperatures of 400°F, 500°F and 600°F
Task V	-	Long-term testing of the most promising seal-material combinations in the 1- and 3-inch rod sizes.
Task VI	-	Development and evaluation of a single-stage high-pressure rod seal in the 1-inch rod size.

Detailed discussion of the progress made in above tasks is presented in the following sections.

TASK I - FACILITIES AND EQUIPMENT

A. FLUID-MATERIAL COMPATIBILITY TEST SETUP

The fluid-material compatibility test apparatus is shown in Figures 1 and 2. The setup consists of a bank of five manifolds, each manifold holding eleven capsules. The capsules in one manifold are all filled with the same hydraulic test fluid; ten of the capsules contain materials for compatibility tests and the eleventh contains fluid for use only as a control sample. All the capsules are immersed in a container filled with molten salt. This entire assembly is placed in an oven and brought up to operating temperature. The molten salt bath ensures a uniform and constant temperature for all the capsules.

Leading from each manifold is a line joined to two manifolds located outside the oven. One of these manifolds is connected to a vacuum pump and is isolated from the other manifold by means of five valves. The second manifold is connected to a shut-off valve and thence to a nitrogen gas supply. The gas used to provide an inert atmosphere is 99.99 percent nitrogen by volume, with an oxygen content of not more than 50 ppm, a hydrocarbon content (methane) of not more than 50 ppm, and a dew point of -90°F or lower. The gaseous nitrogen is admitted into the system through check valves. The purpose of these check valves is to prevent intermixing of vapors from the five test fluids. However, it should be noted that during initial testing it was discovered that the check valves did not provide an effective seal against fluid vapors. To prevent resulting intermixing between manifolds, these valves were replaced with positive shut-off manual valves.

B. SEAL TEST EQUIPMENT

1. Preliminary Seal Test Rig

An existing test rig has been modified to accomplish the preliminary evaluation of seal designs developed during the program. The test rig as shown in Figures 3 and 4 consists of a seal tester, a 3-horsepower variable-speed motor, and a

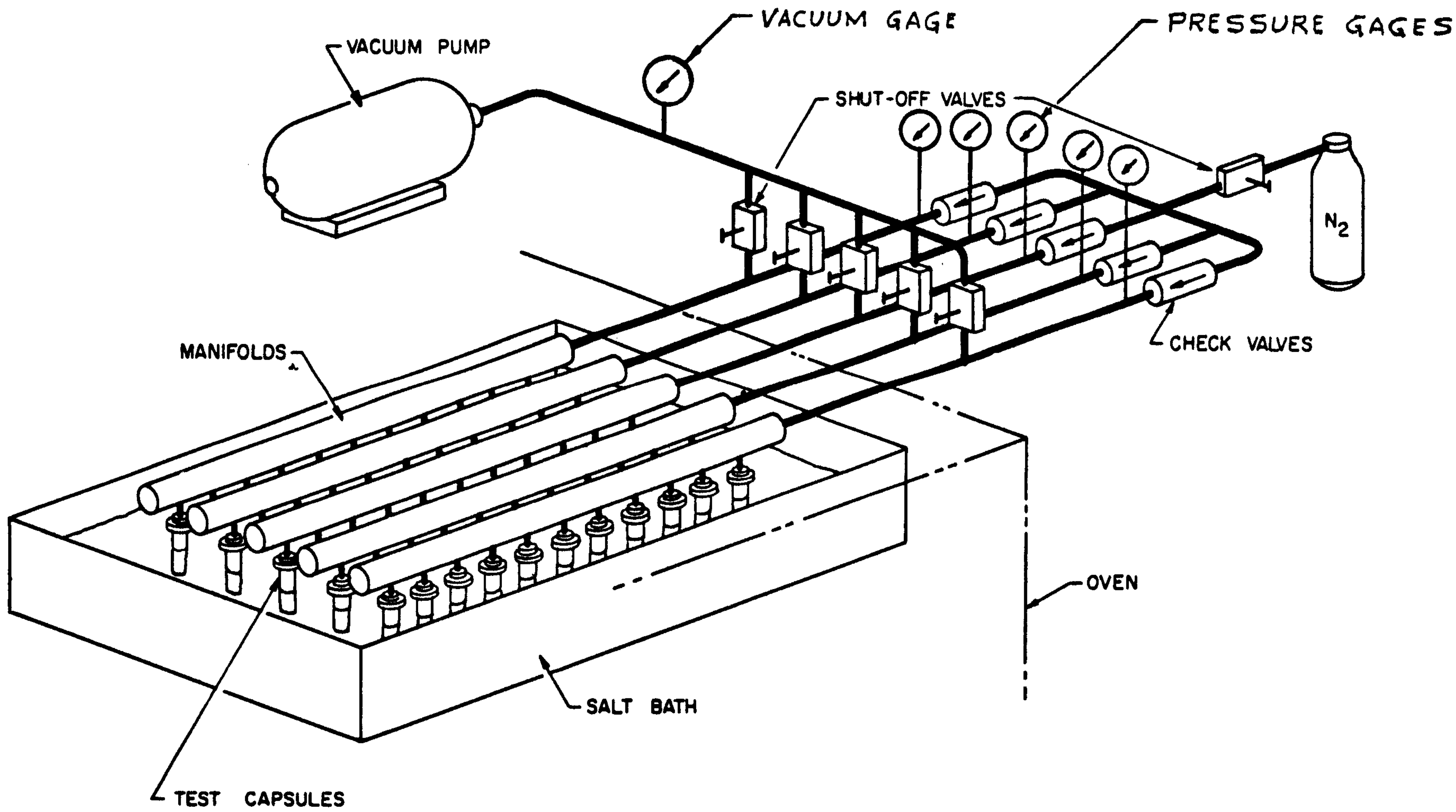

Figure 1. Schematic - Test Setup for Compatibility Tests

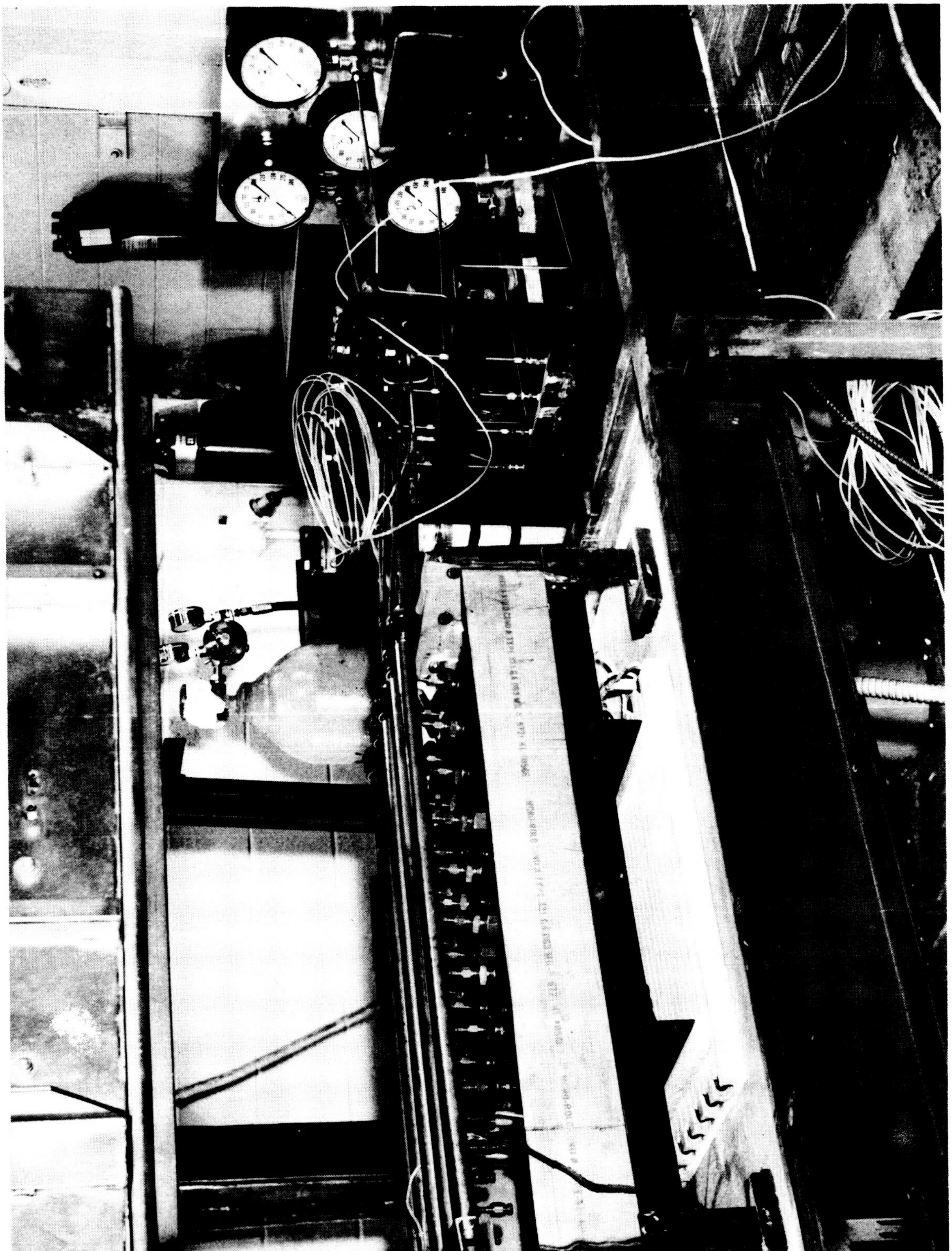

Figure 2. Test Setup for Compatibility Tests

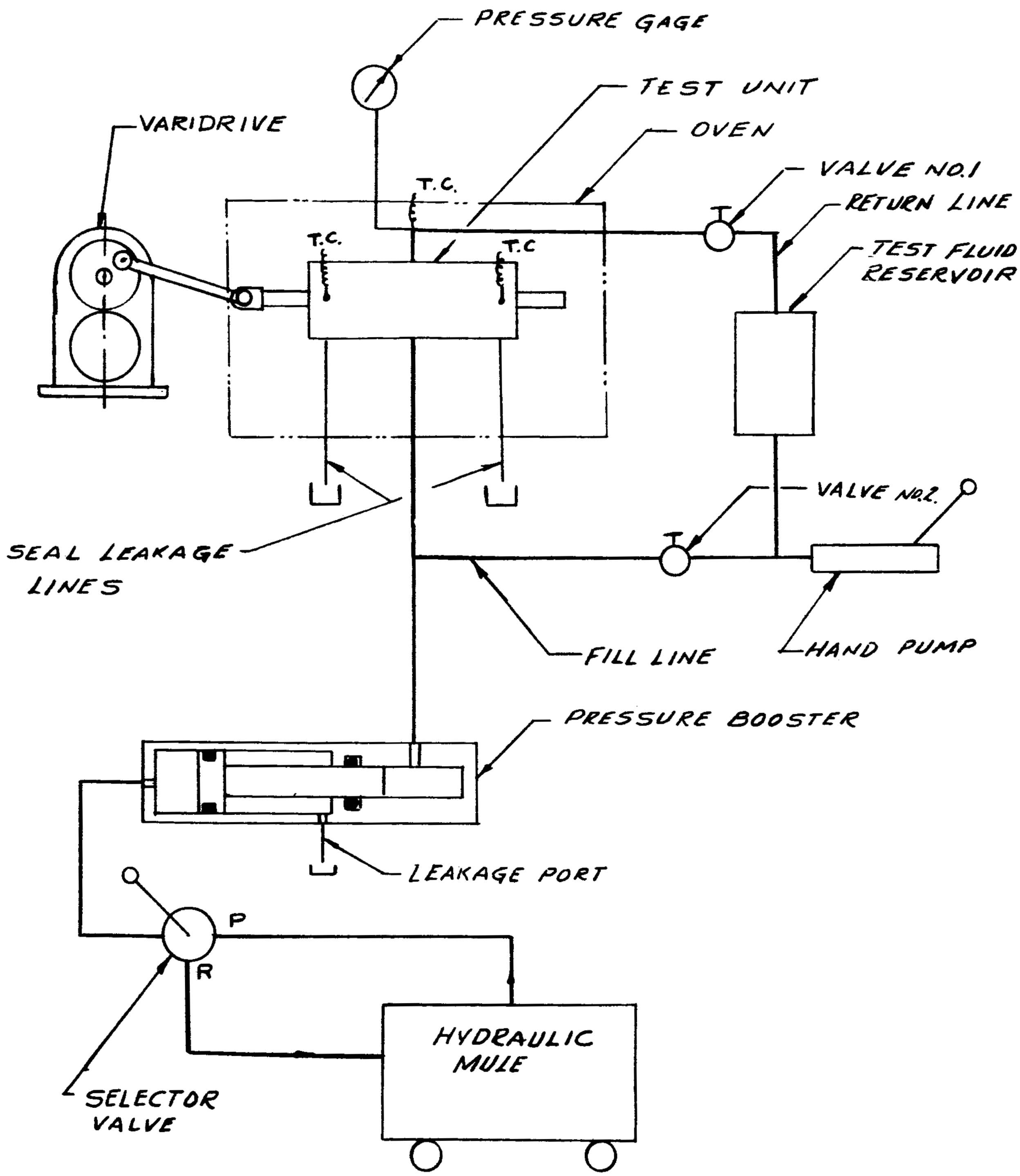

Figure 3. Schematic - Cycling Rig - Preliminary Seal Testing

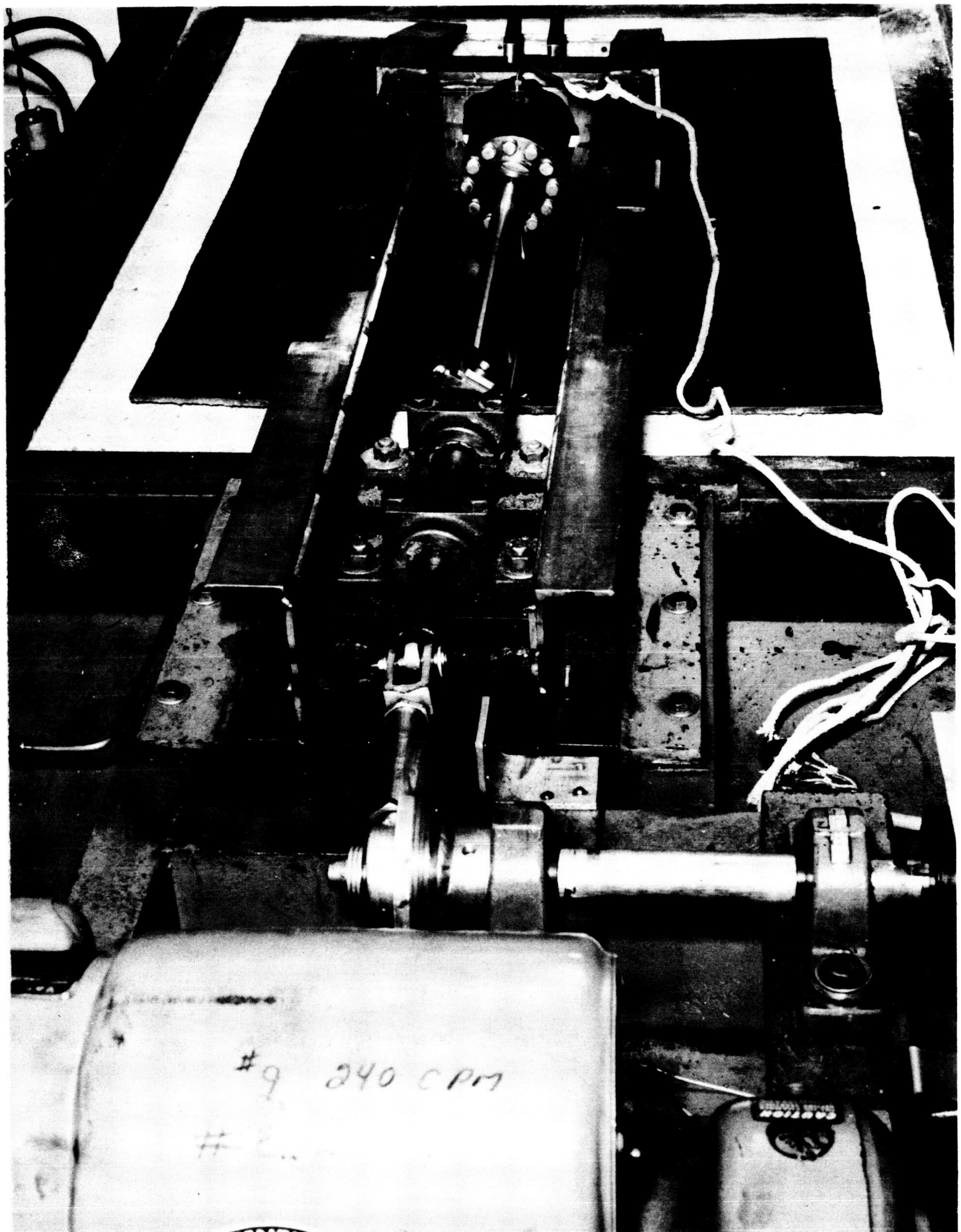

Figure 4. Cycling Rig - Preliminary Seal Testing

hydraulic power source. The hydraulic power source comprises a power circuit and test circuit separated by a barrier cylinder, which also serves as a pressure booster. Although this arrangement is not a strict simulation of any aircraft system, it offers the following distinct advantages for laboratory testing:

- The power can be operated at ambient temperatures, permitting the use of relatively inexpensive components and hydraulic fluid.
- Packing changes in the power system are not required in the event of changing test fluids.
- Total test fluid is limited to a small volume.

The rod seal tester (Figure 5) consists of a cylinder that houses a seal gland on each end. The cylinder and seal glands are constructed of 17-4PH corrosion-resistant steel. The chrome-plated piston rod is fabricated of Type 440C stainless steel. The design of the seal glands permits their adaptation to various seal configurations with only minor modification. Graphite bearings are incorporated in each seal gland to prevent piston rod surface damage due to metal-to-metal contact with the gland shoulder. Premature failure of a seal due to piston rod scoring will thus be minimized.

2. Seal Test Actuators

Design of the 1- and 3-inch seal test actuators for use in both the low pressure and endurance test phases of the program has been completed. Three each of both sizes are being fabricated. A typical test actuator is shown in Figure 6. The actuator consists of a double-ended cylinder with removable seal glands on each end. The actuator housing is fabricated of 17-4PH corrosion-resistant steel. Piston rods are fabricated of Type 440C stainless steel and plated with hard chromium. The seal cavity is designed to accommodate various seal configurations. Leakage ports are located so that leakage from the static and dynamic portion of the rod seal can be measured separately. A barrier seal is provided in the cylinder to simulate the pressure conditions in a typical actuator. For example, during piston rod extension, chamber No. 1 senses high pressures while chamber No. 2 is vented to return. During piston rod retraction, the pressure conditions would be reversed. The advantage of this design is that the piston head is not required, thus eliminating the need for heavy structural members to externally load the actuator.

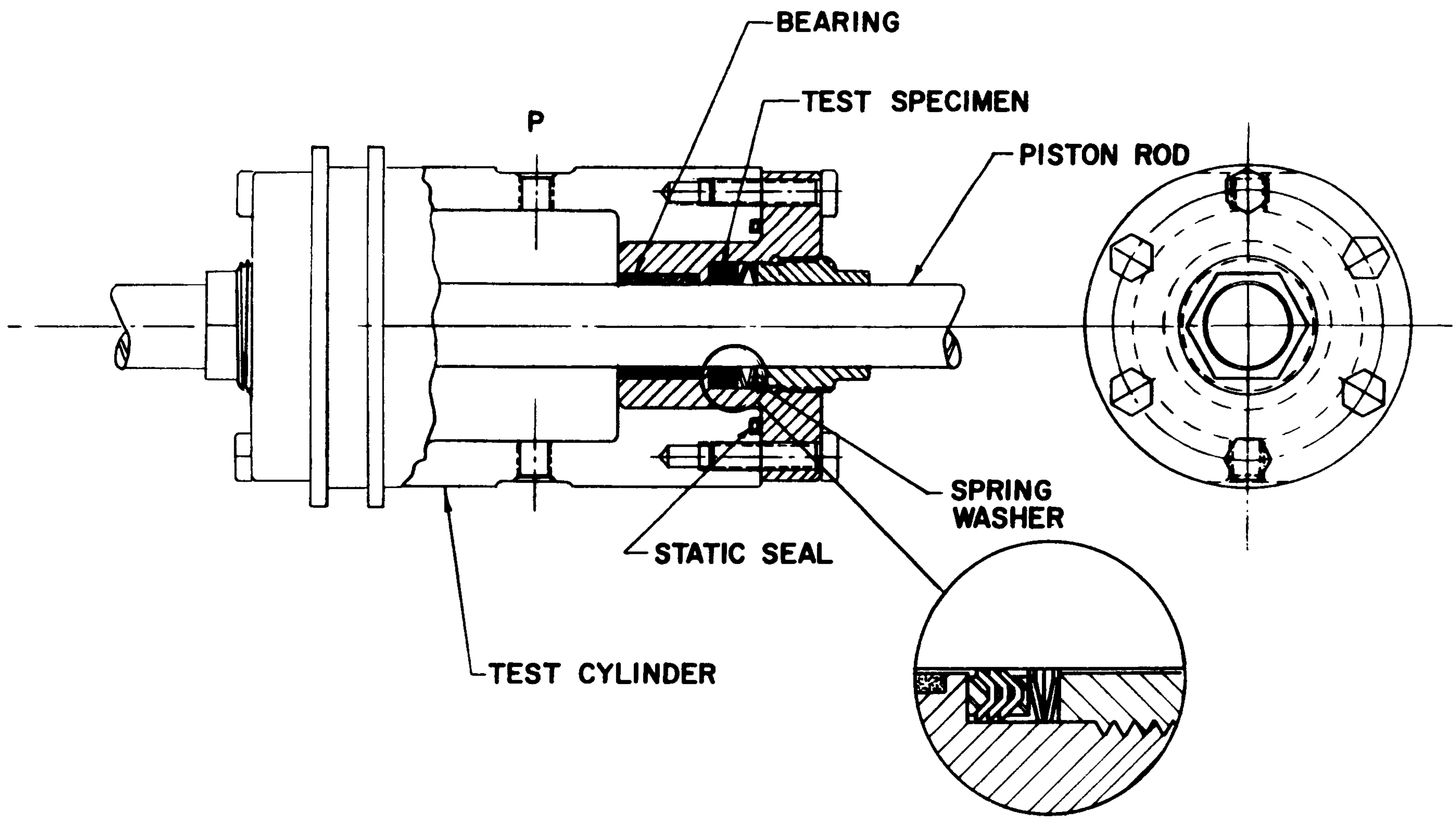

Figure 5. Rod Seal Test Unit

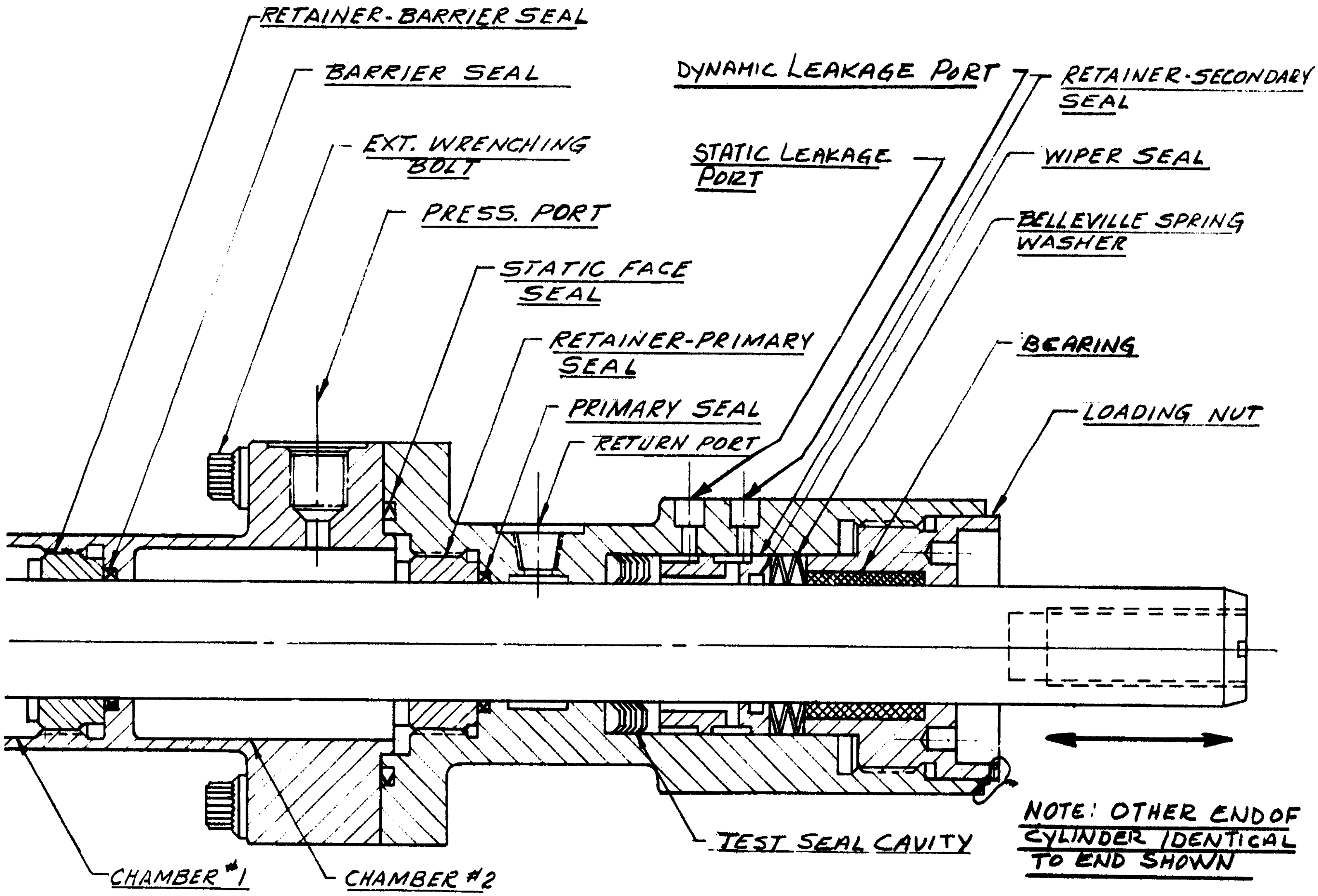

Figure 6. One-Inch Rod Seal Test Unit

The details of the rigs for accommodating the test actuators (Figure 7) have been designed and are being fabricated. These rigs will be used in Tasks IV and V of the program. Two test rigs will be constructed, and each will be partially mounted in an oven with only the test actuator and drive link being subjected to high temperatures. Each endurance test rig will accommodate three test actuators. The actuators will be cycled with a mechanical-input servo-controlled actuator operating through a universal and drive link mechanism. The cycling rate and length of stroke will be varied by adjusting the variable speed drive and the eccentric throw, respectively. A high temperature strain gage tackwelded on the shank of the rod end assembly will be used to measure the seal friction in each actuator. The output of each strain gage will be recorded periodically on a Brush recorder.

3. Reciprocating Wear Tester

A test apparatus was assembled for preliminary evaluation of candidate seal materials, particularly the hard base metals, to determine their wear characteristics when sliding against a hard chrome-plated piston rod.

As shown in Figure 8, the test setup is intended to simulate a reciprocating rod seal arrangement. It consists of a chrome-plated Type 440C stainless steel piston rod and a stationary test specimen. The piston rod is supported on both ends by linear roller bearings. A variable speed motor is used to vary the stroke and reciprocating speed of the piston rod. The configuration of the test specimen consists of a segment of a circle with a radius conforming to the radius of the piston rod. The specimen is mounted in a keyed slider that is attached to the loading arm. A guide block with a thumb screw adjustment permits vertical motion of the arm, but prevents any side motion. Contact pressure between the test specimen and piston rod is varied by varying the weight attached to the loading arm. The assembly will be placed in an enclosure to enable the tests to be conducted in a nitrogen atmosphere.

4. Friction Measurement and Seal Loading Apparatus

The combined friction measurement and seal loading apparatus shown in Figure 9 will be used to obtain experimental data that will aid in the design of the seal and the seal-loading mechanism. Such data will include normal force required

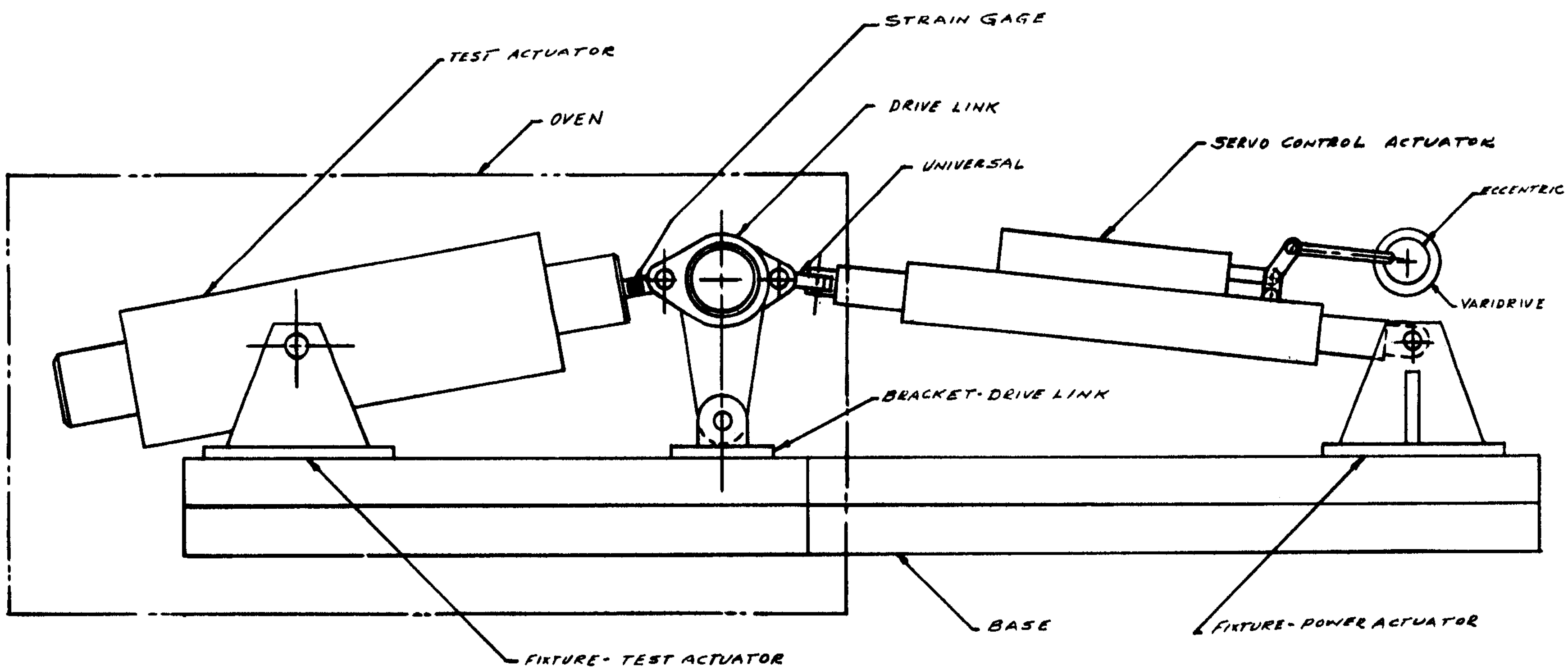

Figure 7. Endurance Test Rig

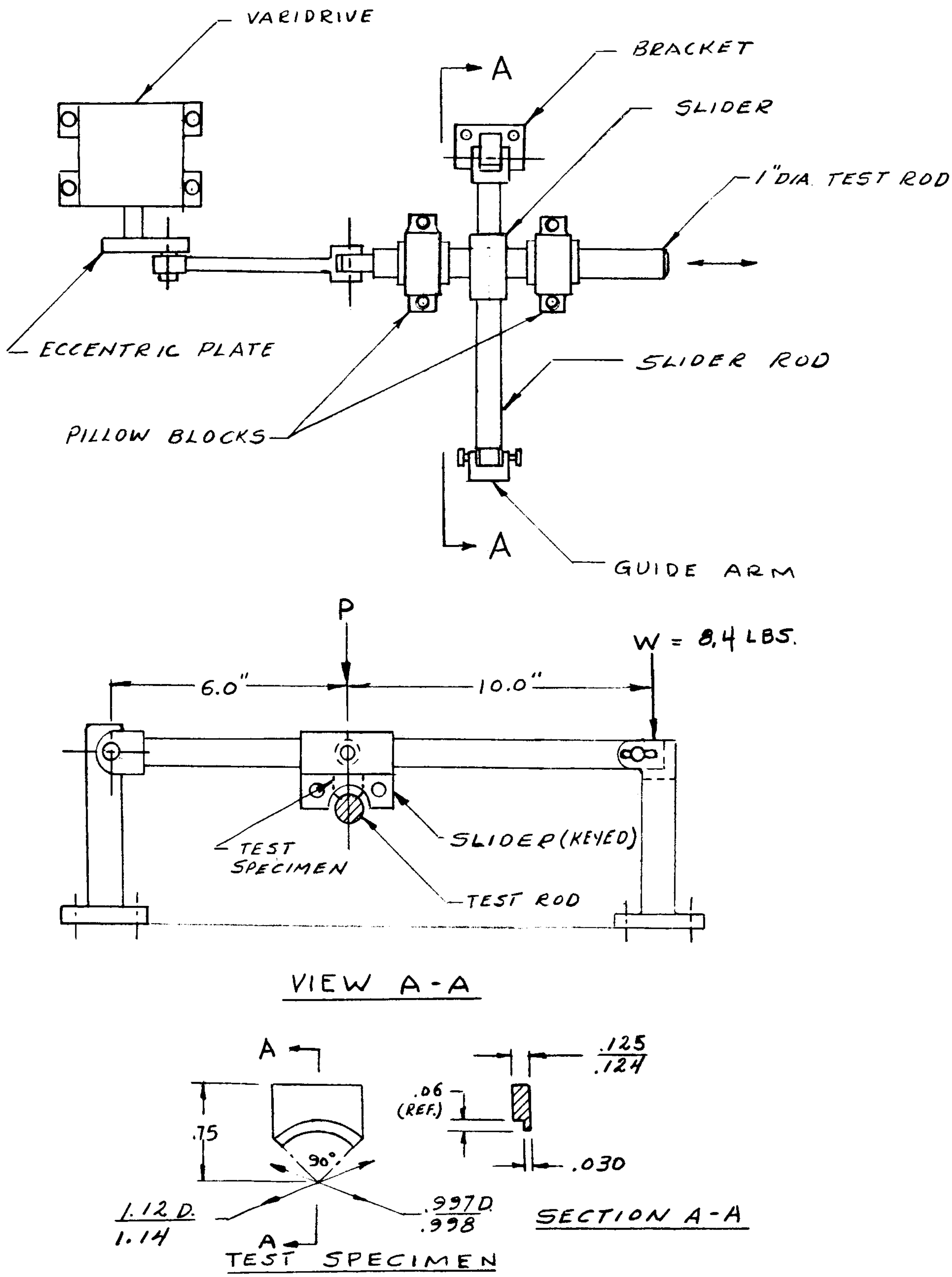

Figure 8. Reciprocating Wear Tester

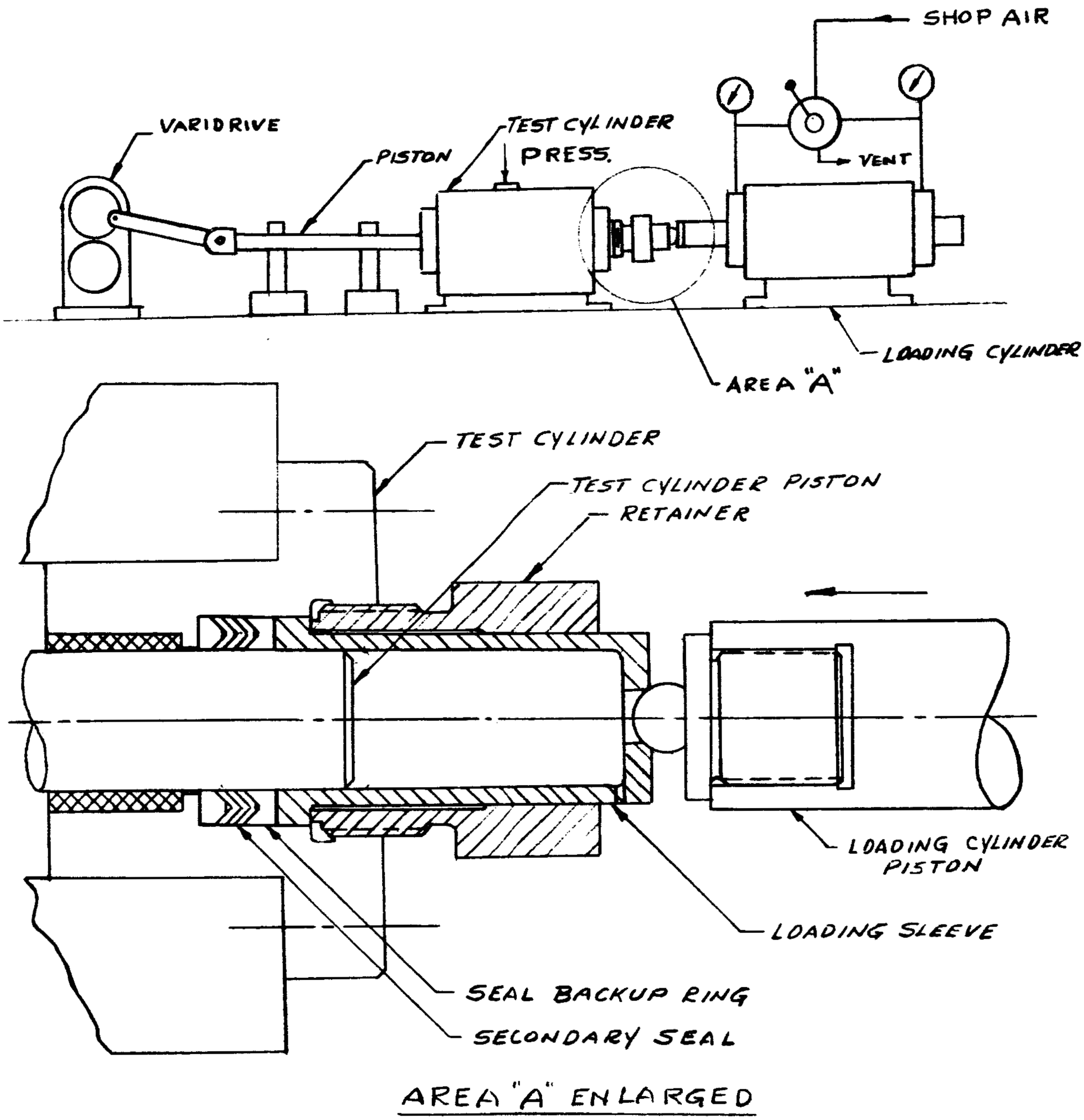

Figure 9. Friction-Measuring and Seal-Loading Apparatus

at the interface to effect a seal at various pressures, and the resultant friction. Behavior of the induced seal load under influence of seal wear can also be determined. As shown in Figure 9, the test setup consists of a seal tester, loading sleeve, and loading cylinder. The seal tester is assembled with a rod seal on each end. Only one seal will be subjected to the load test.

The testing procedure consists of pressurizing the seals to the desired pressure and then gradually loading the seal by applying pressure to the loading cylinder until zero leakage is achieved. The pressure multiplied by the effective area of the cylinder piston determines the load applied axially to the seal. Seal friction is measured with a spring scale. The normal sealing force and resultant contact pressure at the seal interface could then be approximated on the basis of the friction force obtained, friction coefficient, and seal geometry. The effectiveness of the sealing load in compensating for wear will be determined by cycling the piston rod.

TASK II - MATERIALS SELECTION AND EVALUATION

A. MATERIALS SELECTION

In selecting the candidate materials, consideration was given to certain requisites for seal applications. For example, retention of desirable mechanical properties at elevated temperatures, good conformability, and low friction and wear were among the major considerations. Ten (10) materials capable of meeting these requirements were selected jointly by the contractor and NASA and are briefly discussed in the following paragraphs.

1. Polyimide Plastics

Chemically, the polyimides are organic condensation polymers derived from the reaction between pyrometallic dianhydrides and aromatic diamines. In the polyimide group, the unfilled (Polymer SP-1*) material appears to be the most suitable. Rod seals designed from this material were evaluated (Reference 1) for 300 hours at temperatures up to 600°F with no failure. The copper-filled and bronze-filled polyimides are included in the preliminary evaluation phase of the present program as possible alternates. The main drawback to the filled materials is a further decrease in their already limited flexibility

2. Polymet **

This metal/polymeric alloy is composed of silver alloyed during sintering with a fluorocarbon polymer; the resultant material possesses properties of the metal. The polymer content contributes a low coefficient of friction. The alloy also exhibits good wear resistance without lubrication at high temperatures. Promising results were obtained from previous operation at 600°F with rod seals fabricated from this material (Reference 2).

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* DuPont Trademark

** Polymer Corporation of America

3. Silver-Impregnated Metallic Composites

These composites consist of metal fibers that are sintered, brazed, or mechanically interlocked to form a porous metallic skeleton, and then are filled with a relatively soft and pliable material such as silver. This process produces a material that combines the conformability of a soft metal with the strength, creep resistance, and other desirable properties of a stronger material. The concept of fiber reinforcement of a softer matrix is quite applicable to metallic seals for high temperature use where conformability, minimum wear, and high backup strength and resiliency are prerequisites.

Past (Reference 3) and current work on silver composites was reviewed to determine the most suitable composite system. Parameters such as fiber density, diameter, and spacing, and their influence on the strength of the composite structure were analyzed. In essence, the findings reveal that fine fibers (0.0025 inch in diameter) produce a more immediate strengthening of the silver matrix than is produced by the coarse fibers. Closer fiber spacing also gives an increase in strength of the composite. On the basis of these findings, work on silver composites will emphasize the use of fine fiber structures.

For the preliminary test work, fiber bodies consisting of stainless steel (Type 430) and nickel in 30% and 40% densities were procured from the Huyck Corp. Impregnation of these materials with a silver-lithium alloy was accomplished at Republic facilities.

4. Westinghouse Self-Lubricating Composite

This self-lubricating composite (70% silver and 30% tungsten diselenide) offers exceptionally low friction and good wearing qualities. Its thermal coefficient of expansion (6.45×10^{-6} in./in./°F) closely matches that of the Type 440C material proposed for the piston rod.

5. Silver Base Alloys

The candidate alloy selected is a silver-copper eutectic containing 72% silver and 28% copper. Past experience with silver alloys in seal applications has indicated that this eutectic exhibits better wear characteristics than commercially pure silver or coin silver, particularly from the standpoint of metal transfer in sliding applications. An alternate silver-copper alloy with up to 40% copper, which has the effect of raising the tensile strength in the annealed condition from 25,000 psi to 55,000 psi, will also be considered.

6. Nickel Foametal

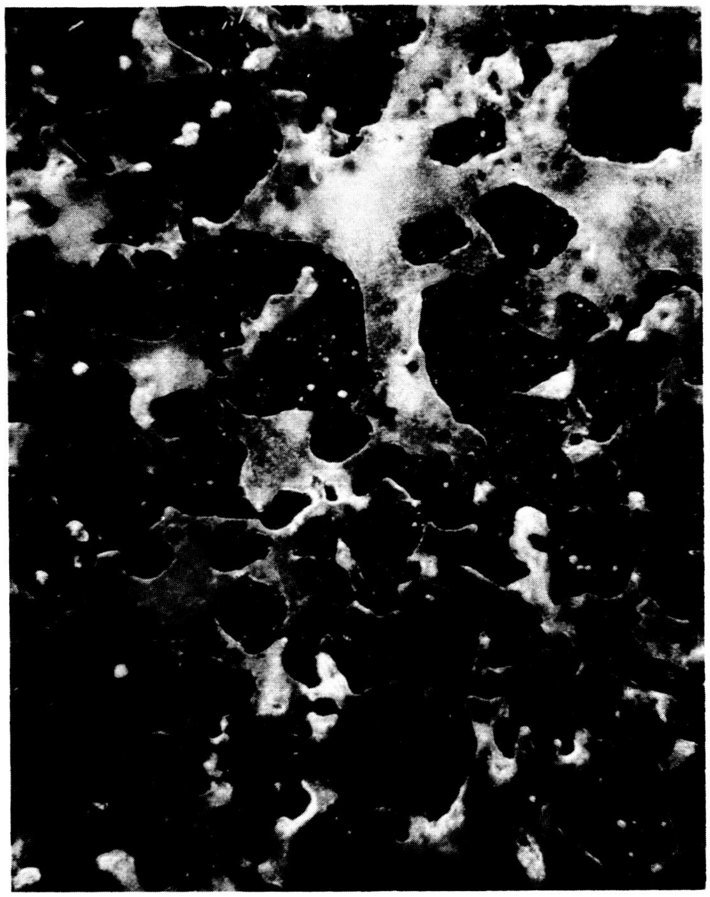
This material is prepared by a metal foaming process developed by General Electric Company's Metallurgical Products Department for abradable seal applications in gas turbine engines. It can be made in a wide range of hardnesses and with densities of between 2% and 75% of the unfoamed metal. Its performance may be enhanced by impregnating with plastics, metals, and ceramics. A 60% dense material was selected. This material was impregnated with a eutectic mixture of calcium fluoride and barium fluoride (see Figure 10). Based on preliminary work conducted by NASA Lewis Research Center (Reference 4), this impregant has exhibited good lubricating qualities and wear resistance.

7. Cobalt Alloy (75% Cobalt, 25% Molybdenum)

Cobalt in its hexagonal form (Reference 5) gives better friction characteristics than the cubic form of the metal in sliding application in vacuum. However, one difficulty encountered in the use of this material is that it undergoes a crystal transformation from hexagonal to the face-centered cubic form at temperatures of approximately 800°F. Initial transformation starts at about 600°F. Alloying cobalt with molybdenum in certain concentrations stabilizes the hexagonal crystalline form of the material.

8. Titanium Alloy (84% Titanium, 16% Tin)

Titanium is an attractive metal for high temperature application because of its high strength-to-weight ratio. Little consideration has been given to this metal for sliding applications because of its relatively poor friction and wear characteristics. However, recent research conducted by NASA (Reference 6) indicates that friction and wear characteristics may be improved by alloying with tin. Friction and wear data (Reference 6) obtained for tin-titanium alloys sliding against 440C in vacuum indicates that the addition of as little as 2.5% tin results in a marked decrease in friction coefficient.



Mag 250 x

Black - Metal
White - Fluoride

Figure 10. Nickel Foametal Impregnated with $C_aF_2 + B_aF_2$

9. Metco Flame-Plated Molybdenum Coating Burnished With MOS_2

This refractory material has been included in this investigation because of its good wear resistance and its good bond strength to most metal substrates. Because of its relatively low coefficient of thermal expansion (approximately 5×10^{-6} in/in/°F), titanium was selected as the base material. The low coefficient of thermal expansion of titanium (as compared to steel) will minimize cracking of the coating due to differential expansion.

10. Vascojet 1000 (H-11 Type Tool Steel)

This alloy has a good combination of toughness and strength at elevated temperatures to 1000°F. An ultimate tensile strength of 268,000 psi can be obtained after air cooling from 1850°F and double tempering at 1050°F. Its nominal composition is 0.40% carbon, 5.0% chromium, 1.30% molybdenum, 0.5% vanadium, and approximately 0.013% sulfur. The presence of sulfur has proven to be beneficial in reducing friction, wear, and metal transfer of tool steels (Reference 7).

11. Alternate Materials

In addition to the above materials, the following alternate possibilities are being considered:

(1) Polymer SP plastics (a - 15% graphite filled, b - 30% bronze filled, and c - 20% copper filled)

(2) Westinghouse composite (75% silver, 20% polyimide, and 5% tungsten diselenide)

(3) Silver impregnated nickel fiber composite

(4) Silver alloy (60% silver, 40% copper)

(5) Elastomers - newly developed elastomers were surveyed for potential materials for high-temperature seal application. The most promising material uncovered during this survey is the perfluoroalkylene-triazine polymer. However, this material is still in the laboratory phase of development and will not be available until early 1966. Another experimental elastomer was brought to the attention of the contractor during the survey, and samples were obtained for evaluation. This material was developed by David Clark Co., Inc., and is designated as Omni Rubber No. X-FVF-19-15.

Limited testing will be conducted with these alternate materials to determine their suitability for seal application.

B. MATERIALS EVALUATION

1. Elastomeric Aging Test

The experimental elastomer (Omni Rubber No. X-FVF-19-15) developed by David Clark Co., Inc., was evaluated. O-rings molded from this material were subjected to oil aging at 400°F with GE F-50 silicone fluid (0 psi) to determine their compression set characteristics. Two O-rings of a standard Viton compound were included in the testing as control samples. The O-rings were installed in fixtures which simulated a rod seal installation. A typical fixture is shown in Figure 11. Testing consisted of aging the specimens in these fixtures at 400°F for 48 hours and checking for compression set.

Testing under the above conditions showed that the experimental compound does not exhibit any improvement over the standard Viton compound. Both O-ring compounds showed 100% compression set after the 48-hour aging period.

2. Materials Compatibility Testing

Compatibility testing of seal materials with the five candidate fluids was initiated with the materials received. Originally, all the candidate materials were to be tested concurrently; however, because of the long lead time required for certain materials, multiple runs were considered to be more expedient. The first compatibility test was conducted at 600°F.

Specimens were fabricated from the following available candidate materials:

(1) Silver-polymer composite (Polymet)

(2) Polyimide - (unfilled)

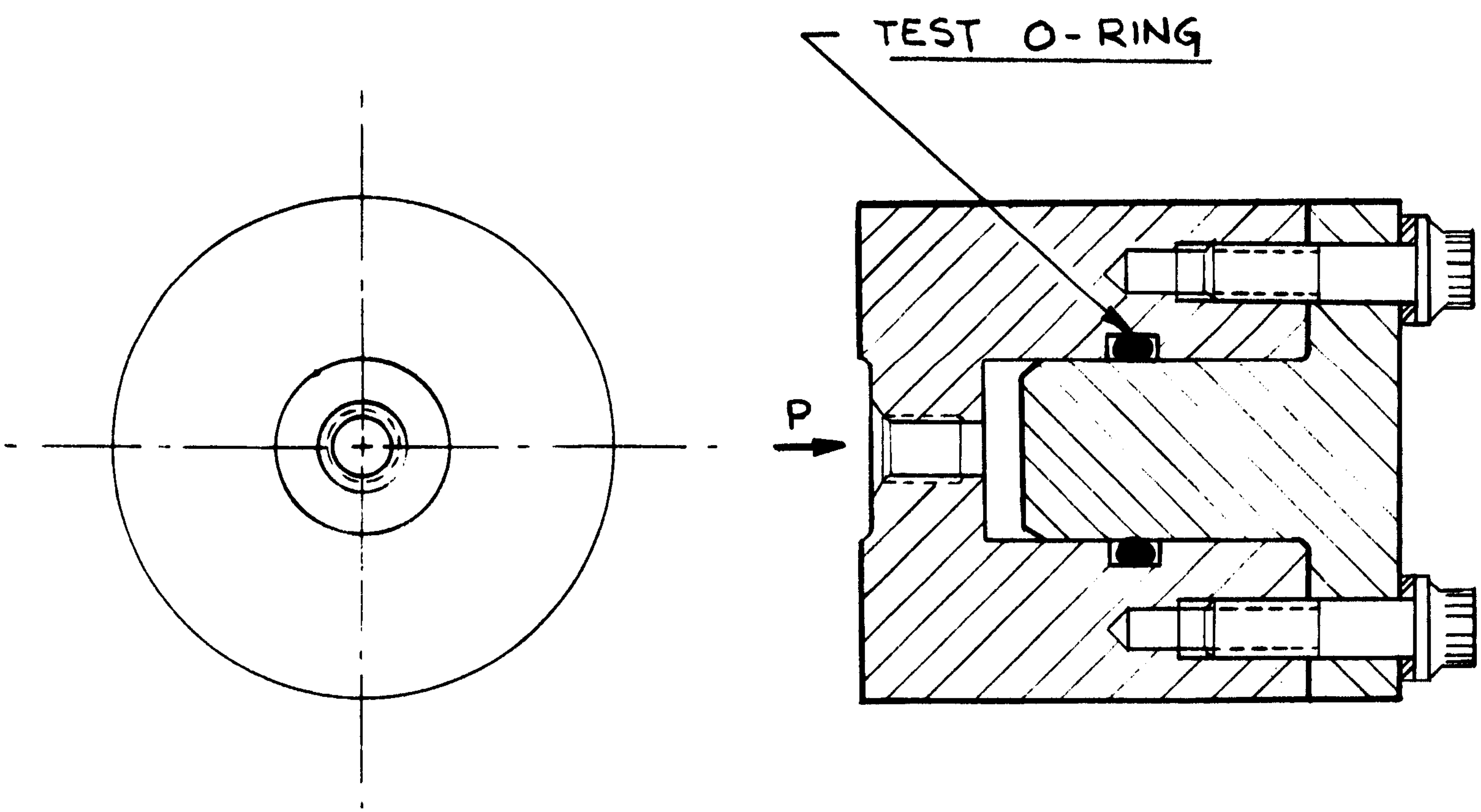


Figure 11. O-Ring Test Fixture

(3) Polyimide - (15% graphite filled)

(4) Polyimide - (30% bronze filled)

(5) Polyimide - (20% copper filled)

(6) NM-100 (Hi-Temp steel alloy)

(7) Silver-impregnated metal composite (430 SS, 35% dense)

The selection of candidate fluids for testing with the above materials was based on the fluids under investigation in the Hydraulic Fluids Evaluation Program (Reference 8). These fluids are:

(1) F-50 Silicone

(2) MCS-3101 Halogenated Polyaryl

(3) MCS-293 Modified Polyphenyl Ether

(4) PR-143-AB Fluorocarbon

(5) MLO-60-294 Super Refined Mineral Oil

Hardness readings were taken on the bulk material prior to machining the specimens. Each specimen was weighed prior to testing.

As shown in Figure 12, the test specimen, which is approximately 7/8 inch in diameter, is kept in face contact with a polished, hard chromium-plated stainless steel button by means of a screw and spring assembly. This arrangement provides a constant contact pressure between the test specimen and button at elevated temperatures.

Each specimen was inserted in a capsule as shown in Figure 13. The capsules were fabricated from one-inch diameter stainless steel tubing with flared ends for attaching AN919-21 reducers (one-inch to 1/4-inch tube size). Stainless steel was selected as the capsule material because it is most representative of the seal environment during operation in flight actuators. The capsules in each manifold (see Figure 1), were filled with the same hydraulic test fluid. Seven of the capsules contained materials for compatibility tests and the eighth contained fluid for use only as a control sample. Approximately 30 ml of fluid were used in each capsule.

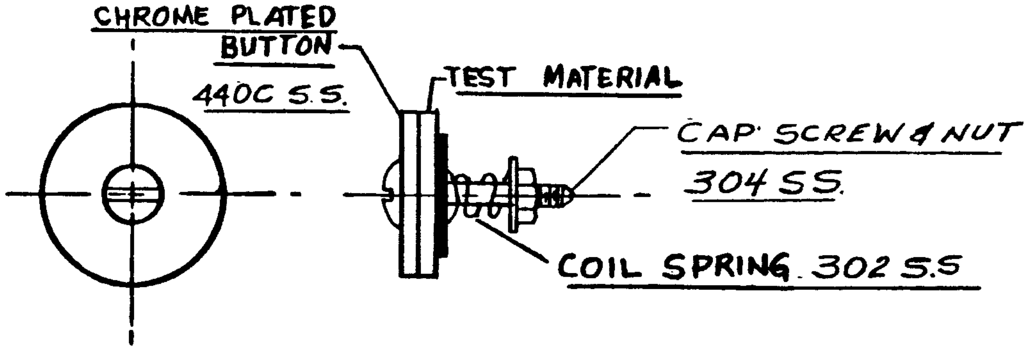


Figure 12. Test Specimen Assembly

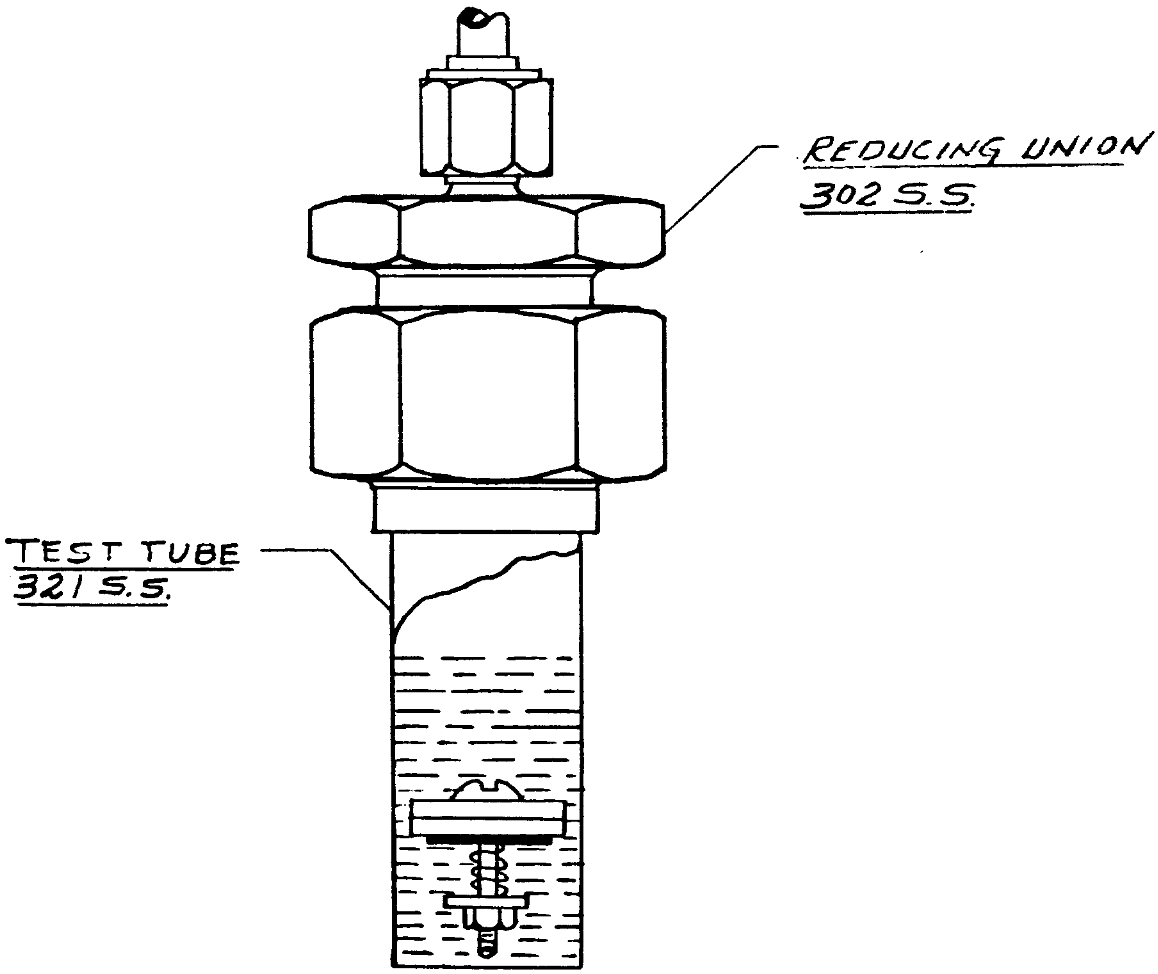


Figure 13. Test Capsule

As the first step in the compatibility tests, the fluids were degassified for 72 hours at a vacuum of 29 inches of Hg. This was accomplished by drawing a vacuum in the system after the fluids have been warmed slightly. After degassification, the five vacuum isolating valves were closed and approximately one atmosphere of nitrogen was admitted into the system through check valves.

With the exception of the MCS-3101, all of the fluids completed the 150-hour test. Evidence of degradation of the MCS-3101 was noticed after 95.5 hours at 600°F when pressure in the manifold built up from 15 psi to 210 psi. Consequently, this fluid was removed from the test. Prior to the removal of this fluid, gas samples were collected from the manifold when pressure initially built up to 62 psi and again at 210 psi. These samples were shipped to Monsanto for analysis. However, the results of the analysis were inconclusive because of the presence of a large amount of air. It is believed that the air was introduced during gas sampling. Visual inspection of the fluid showed considerable sludge formation accompanied by a strong acidic odor.

The data resulting from the compatibility test is summarized in Tables 1 through 5. The appearance of the material specimens are shown in Figure 14. In general, the most compatible fluid with this group of materials is the MLO-60-294, followed by PR-143-AB and MCS-293. The F-50 was fairly compatible with the polyimide base materials and the silver-polymer (Polymet) composite. The side of the NM-100 steel alloy and silver-stainless steel composite not in contact with the hard chrome plate was corroded by the F-50. However, the NM-100 surface mating with the chrome-plate disc exhibited no change in appearance, whereas the mating surface of the silver-stainless steel composite exhibited a tarnished appearance.

The MCS-3101 was not compatible with any of the materials tested. The specimens showed evidence of oxidation and also exhibited a coating of baked oil. Considerable corrosion was exhibited by the NM-100 steel alloy and the silver-stainless steel composite material on the side opposite the chrome-plated disc.

TABLE 1

FLUID - MATERIAL COMPATIBILITY TEST NO. 1 - 150 HRS. @ 600°F
MCS-3101 HALOGENATED POLYARYL FLUID
30 ML PER TEST SPECIMEN

SPECIMEN	Polymet Ag	Polyimide (Unfilled)	Polyimide (Graphite)	Polyimide (Bronze)	Polyimide (Copper)	NM-100	Silver-SS Composite	Control
Weight Change of Specimen (Grams)	+.1677	+.0136	+.0367	+.5426	+.2281	-.0141	-.0679	
** Hardness Change	From H-48 to H-24	From H-90 to H-97 spec. cracked	From H-86 to H-85	From H-97 to H-70 spec. cracked	Specimen cracked	From C-38.5 to C-41.5	From H-97.5 to H-60.0	
Appearance of Specimen	Deposit of burnt oil	Darkened	Darkened deposit of burnt oil	Corroded, pitted, oxidized	Corroded, pitted, oxidized	Corroded	Corroded and pitted	
Appearance of Mating Surface	Deposit of burnt fluid. Heavy corrosion on unplated side.	Heavy deposit. Unplated side heavily corroded.	Discolored, uniform black deposit. Unplated side heavily corroded.	Heavy black deposit. Unplated side heavily corroded.	Heavy black deposit. Unplated side heavily corroded.	Heavy black deposit. Unplated side heavily corroded.	Uniform black deposit. Unplated side heavily corroded.	
Appearance of Fluid	Extremely viscous and black	Extremely viscous and black	Extremely viscous and black	Extremely viscous and black	Extremely viscous and black	Extremely viscous and black	Extremely viscous and black	Extremely viscous and black
Viscosity @ 100°F, CS (4.34)	-	-	-	-	-	-	-	-
Viscosity @ 210°F, CS (1.32)	-	-	-	-	-	-	-	-
Acid No. mg KOH/g (0.11)	-	-	-	-	-	-	-	*

* Fluid severely degraded and shipped to Monsanto for analysis.

** Rockwell-C and Rockwell-H scale

TABLE 2

FLUID - MATERIAL COMPATIBILITY TEST NO. 1 - 150 HRS. @ 600°F MLO-60-294 SUPER REFINED MINERAL OIL FLUID 30 ML PER TEST SPECIMEN

SPECIMEN	Polymet Ag	Polyimide (Unfilled)	Polyimide (Graphite)	Polyimide (Bronze)	Polyimide (Copper)	NM-100	Silver-SS Composite	Control
Weight Change of Specimen (Grams)	+.0069	-.0038	-.0077	-.0166	-.0072	-.0024	+.0015	
* Hardness Change	From H-48 to H-53	From H-90 to H-83	From H-86 to H-77	From H-97 to H-90	From H-89 to H-83	From C-38.5 to C-43	From H-97.5 to H-90.0	
Appearance of Specimen	No change on side mating with chrome disc, discolored on opposite side.	Slightly darkened	Slightly darkened	Slightly darkened	Slightly darkened	Discolored	No change	
Appearance of Mating Surface	No change. Unplated side discolored.	No change. Unplated side slightly discolored.	No change. Unplated side slightly discolored.	No change. Unplated side slightly discolored.	Slight discoloration on both sides.	No change. Unplated side discolored.	No change. Unplated side discolored.	
Appearance of Fluid	Dark amber	Dark amber	Dark amber	Dark amber	Dark amber	Dark amber	Dark amber	Dark amber
Viscosity @ 100°F, CS (15.02)	10.32	10.76	10.85	10.76	10.63	10.88	9.75	10.96
Viscosity @ 210°F, CS (3.26)	2.61	2.76	2.66	2.61	2.67	2.62	2.59	2.73
Acid No. mg KOH/g (0.02)	0.06	0.05	0.05	0.05	0.04	0.08	0.05	0.12

* Rockwell-C and Rockwell-H scale

TABLE 3

FLUID - MATERIAL COMPATIBILITY TEST NO. 1 - 150 HRS. @ 600°F
PR-143-AB FLUOROCARBON FLUID
30 ML PER TEST SPECIMEN

SPECIMEN	Polymet Ag	Polyimide (Unfilled)	Polyimide (Graphite)	Polyimide (Bronze)	Polyimide (Copper)	NM-100	Silver-SS Composite	Control
Weight Change of Specimen (grams)	+.0091	-.0062	-.0124	-.0259	-.0138	+.0004	+.1326	
* Hardness Change	From H-48 to H-41	From H-90 to H-85	From H-86 to H-75	From H-97 to H-93	From H-89 to H-80	From C-38.5 to C-43.5	From H-97.5 to H-61.0	
Appearance of Specimen	No change	Slight darkening	Slight darkening	Slight darkening	Slight darkening	Slight discoloration	Discolored on side mating w/chrome disc. corroded on opposite side.	
Appearance of Mating Surface	No change. Heavy corrosion on unplated side.	No change. Unplated side heavily corroded.	Green deposit. Unplated side heavily corroded.	Discolored. Unplated side heavily corroded.	Discolored. Unplated side heavily corroded.	Discolored. Unplated side heavily corroded	Discolored, heavy deposit. Unplated side heavily corroded.	
Appearance of Fluid	Cloudy with a top layer of dark amber fluid.	Cloudy with a top layer of dark amber fluid.	Cloudy with a top layer of dark amber fluid.	Cloudy with a top layer of dark amber fluid.	Cloudy with a top layer of dark amber fluid.	Cloudy with a top layer of dark amber fluid.	Cloudy with a top layer of dark amber fluid.	Cloudy with a top layer of dark amber fluid.
Viscosity @ 100°F., CS (60.13)	58.07	59.13	62.81	59.72	56.34	56.94	59.27	59.88
Viscosity @ 210°F., CS (7.94)	8.16	7.89	8.53	8.30	7.79	8.24	7.87	8.21
Acid No. mg KOH/g	Standard method of test for neutralization number by potentiometric titration (ASTM D664-58) is not applicable with this fluid.							

* Rockwell-C and Rockwell-H scale

TABLE 4

FLUID - MATERIAL COMPATIBILITY TEST NO. 1 - 150 HRS. @ 600°F
MCS-293 - MODIFIED POLYPHENYL ETHER FLUID
30 ML PER TEST SPECIMEN

SPECIMEN	Polymet Ag	Polimide (Unfilled)	Polyimide (Graphite)	Polyimide (Bronze)	Polyimide (Copper)	NM-100	Silver-SS Composite	Control
Weight Change of Specimen (Grams)	+.0118	-.0062	-.0025	-.0266	-.0153	+.0868	-.0005	
* Hardness Change	From H-48 to H-49	From H-90 to H-87	From H-86 to H-74	From H-97 to H-92	From H-89 to H-80	From C-38.5 to C-46	From H-97.5 to H-83.0	
Appearance of Specimen	No change	Darkened	No change	Slight pitting	No change	No change on side mating with chrome disc. Corrosion on opposite side.	Tarnished on side mating with chrome disc. Corrosion on opposite side.	
Appearance of Mating Surface	Discolored Slight deposit. Corroded on unplated side.	Greenish deposit. Unplated side corroded.	Discolored. Slight uniform deposit. Unplated side corroded.	Heavy dark deposit. Unplated side corroded.	Slight deposit. Unplated side corroded.	Greenish deposit. Unplated side corroded	Greenish deposit. Unplated side corroded.	
Appearance of Fluid	Dark brown	Dark brown	Dark brown	Dark brown	Dark brown	Dark brown	Dark brown	Dark brown
Viscosity @ 100°F, CS (48.18)	66.54	284.84	395.13	128.39	82.30	145.99	45.14	246.79
Viscosity @ 210°F, CS (15.99)	31.13	62.63	78.87	35.95	24.18	54.58	17.36	56.16
Acid No. mg KOH/g (0.03)	0.30	0.30	0.20	0.30	2.68	3.38	6.42	6.70

* Rockwell-C and Rockwell-H scale

TABLE 5

FLUID - MATERIAL COMPATIBILITY TEST NO. 1 - 150 HRS. @ 600°F
F-50 SILICONE BASE FLUID
30 ML PER TEST SPECIMEN

SPECIMEN	Polymet Ag	Polyimide (Unfilled)	Polyimide (Graphite)	Polyimide (Bronze)	Polyimide (Copper)	NM-100	Silver-SS Composite	Control
Weight Change of Specimen (Grams)	+.0040	-.0028	-.0041	+.0070	+.0011	+.0007	+.0071	
* Hardness Change	From H-48 to H-43	From H-90 to H-89	From H-86 to H-78	From H-97 to H-84	From H-89 to H-79	From C-38.5 to C-43.0	From H-97.5 to H-70.5	
Appearance of Specimen	Slightly discolored	No change	No change	Discolored, surface roughened	Discolored, dark deposit	Slightly darkened	Darkened and roughened	
Appearance of Mating Surface	No change. Slight discoloration on unplated side.	No change. Slight discoloration on unplated side.	No change. Slight discoloration on unplated side.	No change. Slight discoloration on unplated side.	Slight discoloration. Unplated side slightly discolored.	Slight deposit. Unplated side slightly discolored.	Discolored. Slight deposit. Unplated side slight deposit.	
Appearance of Fluid	Light brown	Light brown	Light brown	Light brown	Light brown	Light brown	Light brown	Light brown
Viscosity @ 100°F, CS (25.30)	28.26	28.62	29.13	24.48	27.91	28.92	28.11	28.50
Viscosity @ 210°F, CS (4.18)	4.50	4.54	4.52	4.13	4.59	4.50	4.47	4.59
Acid No. mg KOH/g (0.01)	0.03	0.03	0.04	0.03	0.04	0.05	0.05	0.05

* Rockwell-C and Rockwell-H scale

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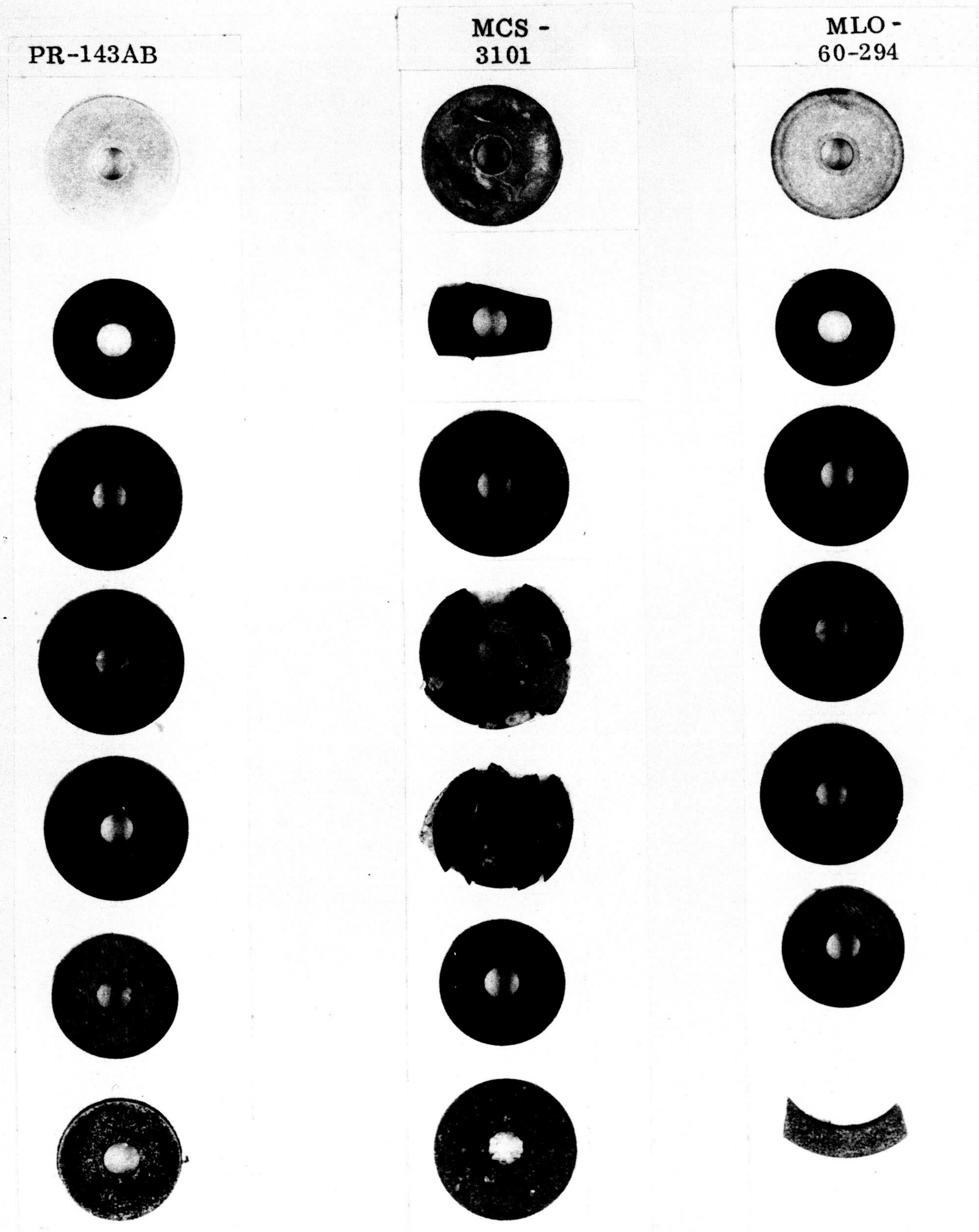

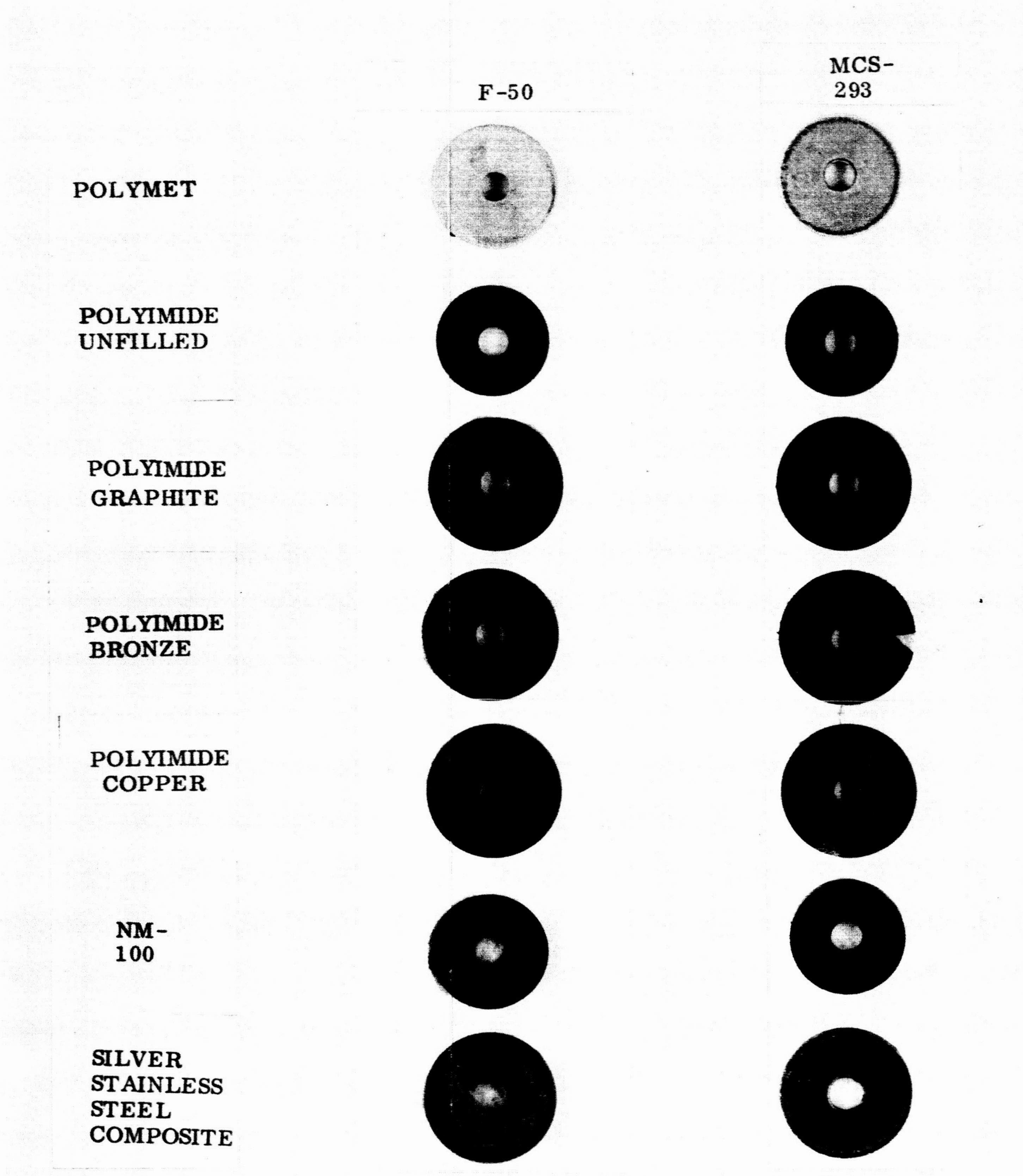

Figure 14. Test Specimens

Inspection of the chrome-plated mating buttons indicated that some form of protective coating is necessary on Type 440C stainless steel to prevent its corrosion in the presence of F-50, MCS-3101, MCS-293, and PR-143AB fluids when subjected to elevated temperatures. Corrosion in various degrees was observed on the unplated side of the test disc with these fluids. In the case of the MLO-60-294 mineral oil, only slight discoloration occurred.

Viscosity values at 100°F and 210°F, as well as the acid numbers at room temperature, were obtained for all the fluids except the MCS-3101. This fluid, which degraded after 95.5 hours at 600°F, was sent to Monsanto for analysis. The MLO-60-294 decreased in viscosity at 100°F and 210°F (29% and 18%, respectively) but increased slightly in acidity. Its effect on the appearance of the test specimens was limited to a slight darkening in some cases with no change in the others. The viscosity change of the PR143AB fluid was negligible. The acid numbers for this fluid could not be determined because the standard method (ASTM D664-58) was not applicable. Slight variations in the viscosity and acid number were exhibited by the MCS-293 fluid. The appearance of the fluid samples is shown in Figures 15 and 16.

A condiderable increase in viscosity was experienced by the F-50 silicone fluid. The acid numbers obtained were unusually high for the control fluid sample and the fluid samples containing the copper-filled polyimide, the NM-100, and the silver-stainless steel composite.

It was noted that a slight intermixing of the fluids had occurred during the test. The presence of a second fluid was very apparent in the PR-143AB because of the difference in density and the water-like appearance of the fluid. The small quantity of fluid (approximately 1 cc) floating on top of the PR-143AB was tentatively identified as MLO-60-294, because of its appearance and proximity to the PR-143AB test manifold. It is conceivable that fluid intermixing occurred in the other manifolds. However, this was difficult to ascertain visually because of the opaqueness of these latter fluids. Intermixing was caused by leakage past the check valves (see Figure 1). The test setup was reworked to replace the check valves with positive-closing manual shutoff valves.

Figure 15. MCS-293 and MLO-60-294 Fluids After Testing at 600°F

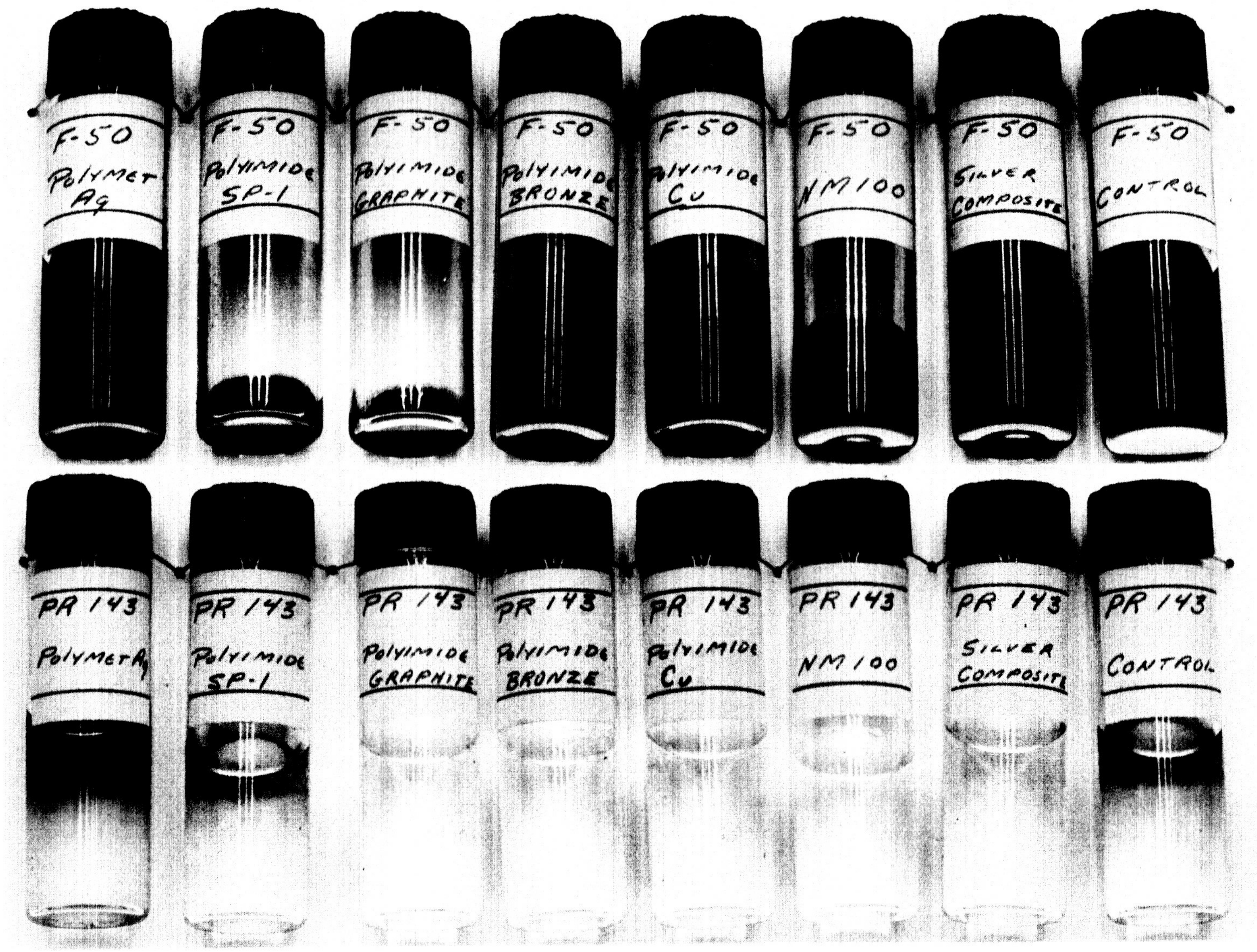

Figure 16. F-50 Silicone and PR-143-AB Fluids After Testing at 600° F

Based on the foregoing results and the thermal stability test reported in NASA CR-54492 (Reference 8), it was agreed with the NASA Project Manager that further testing of the MCS-3101 fluid at 600°F be discontinued.

Preparation of material specimens for the second compatibility test at 600°F is in progress. The candidate materials are:

(1) Westinghouse composite RB-HI-1 (75% silver, 20% polyimide, 5% tungsten diselenide)

(2) Silver alloy (72% silver, 28% copper)

(3) Westinghouse composite RB-AGI-1 (70% silver, 30% tungsten diselenide)

(4) Silver impregnated stainless steel (Type 430) fiber composite

(5) Silver impregnated nickel fiber composite

(6) Nickel Foametal (60% density, impregnated with a eutectic mixture of calcium fluoride and barium fluoride)

(7) Vascojet-1000 (H-11 tool steel)

(8) Titanium alloy (84% titanium, 16% tin)

(9) Cobalt alloy (75% cobalt, 25% molybdenum)

(10) Metco flame-plated molybdenum burnished with molybdenum disulphide (AMS-4908A titanium base material)

These materials will be evaluated with MLO 60-294, F-50, MCS-293 and PR-143AB. As previously mentioned, the MCS-3101 fluid will not be used in the 600°F testing. However, provisions have been made to evaluate a limited number of seal materials with MCS-3101 at 600°F; to verify some of the results obtained in the previous test. The material specimens and the MCS-3101 fluid will be contained in separate test capsules completely isolated from the basic test apparatus.

3. Mechanical Properties Testing

The tensile properties of the candidate materials are being obtained. The materials tested to date are summarized in Table 6. Because of the high cost of most of these materials, a scaled-down tensile specimen was used to conserve materials. All testing was done on an Instron test machine in air at 600°F, using quartz radiant lamps as the heat source. The time to temperature was approximately 10 minutes, and the time at temperature was 3 to 5 minutes. Temperature sensing was by means of a chromel-alumel thermocouple wrapped around the gage length of the test specimen. The specimens were tested at a strain rate of 0.02 in./in. to the yield and increased to 0.2 in./in. from the yield to fracture. The yield strength was obtained at 0.2% offset.

A comparative evaluation of these materials will be conducted as soon as properties data are obtained for all candidate materials.

TABLE 6

PROPERTIES OF CANDIDATE MATERIALS

Mechanical Properties at 600°F	Polymer SP-1	Polymet	Silver Composite 430 SS, 30% dense	Silver Composite Nickel,* 30% dense	Consil-720 Silver Alloy 72% - 28%	Consil-600 Silver Alloy,* 60% - 40%	Vascojet-1000 (H-11)	Nickel Foametal 60% dense Impregnated w/Ca F_2 and Ba F_2
**** Modulus of Elasticity (psi)	15.0×10^4	1.44×10^5	5.47×10^6	10.8×10^6	6.0×10^6	7.5×10^6	23.9×10^6	9.07×10^6
**** Yield Strength .2% offset (psi)	1285	3444	11,525	12.277	21,325	30,997	183×10^3	8297
Ultimate Tensile (psi)	1325	5805	18,762	19,333	32,550	41,361	225×10^3	8,297
% Elongation	3.25%	7.6%	8.7%	11.5%	15.8%	24.7	1.8%	2.45%
Hardness**	Rockwell H-83-89	Rockwell H-53	Rockwell H-90	Rockwell H-83	Rockwell F-89	Rockwell H-97	Rockwell C-52	Rockwell F-87
Coefficient of Friction	*** 0.08 - 0.15	*** 0.06 - 0.14						
Thermal Coefficient of Expansion (in./in./°F	29.8×10^{-6}	8.9×10^{-6}					6.8×10^{-6}	

* Alternate material

** Hardness readings obtained at room temperature

*** Vendor's data

**** In tension

TASK III - SEAL DESIGN AND DEVELOPMENT

A. DESIGN APPROACH

To meet the low external leakage and long life requirements of this program, primary consideration is being given to a two-stage seal design. In this approach, the first-stage (high pressure) seal is subjected to the full operating pressure, and a controlled amount of internal leakage is returned to the system reservoir. The second-stage (low pressure) seal is subjected only to the system return pressure, and has practically zero external leakage. First-stage seal leakage is kept to a minimum, because the large number of actuators used in a flight vehicle would otherwise present a substantial tare power drain on the system.

The approach to the first-stage seal is to use split-ring contracting rod seals. Experience has shown that this type of seal can provide effective sealing with acceptable leakage. Hydraulic balancing to reduce wear and friction can readily be accomplished with these sealing rings.

For the second stage, consideration is being given mainly to positive contact type seals. This approach has the greatest potential of meeting the leakage requirement of one drop per minute. A major portion of the design effort will be devoted to the second-stage seal because of its more stringent leakage requirements.

Design concepts for the low pressure and high pressure stages are discussed in the following subsection.

B. LOW PRESSURE SEAL DESIGN

1. Seal Designs for Plastic Materials

The seal designs shown in Figures 17 and 18 are intended for use with the Polymer SP plastic. These designs fully utilize the relatively high elastic properties and conformability of the material to effect a seal. The seal shown in

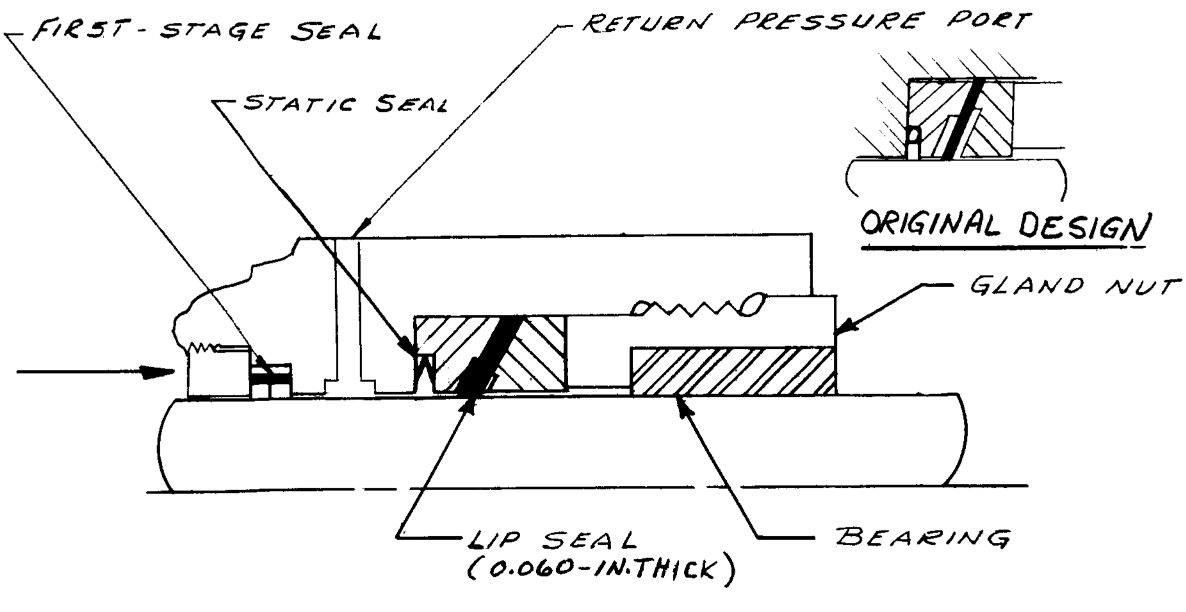

Figure 17. Polymer SP Lip Seal-Low Pressure

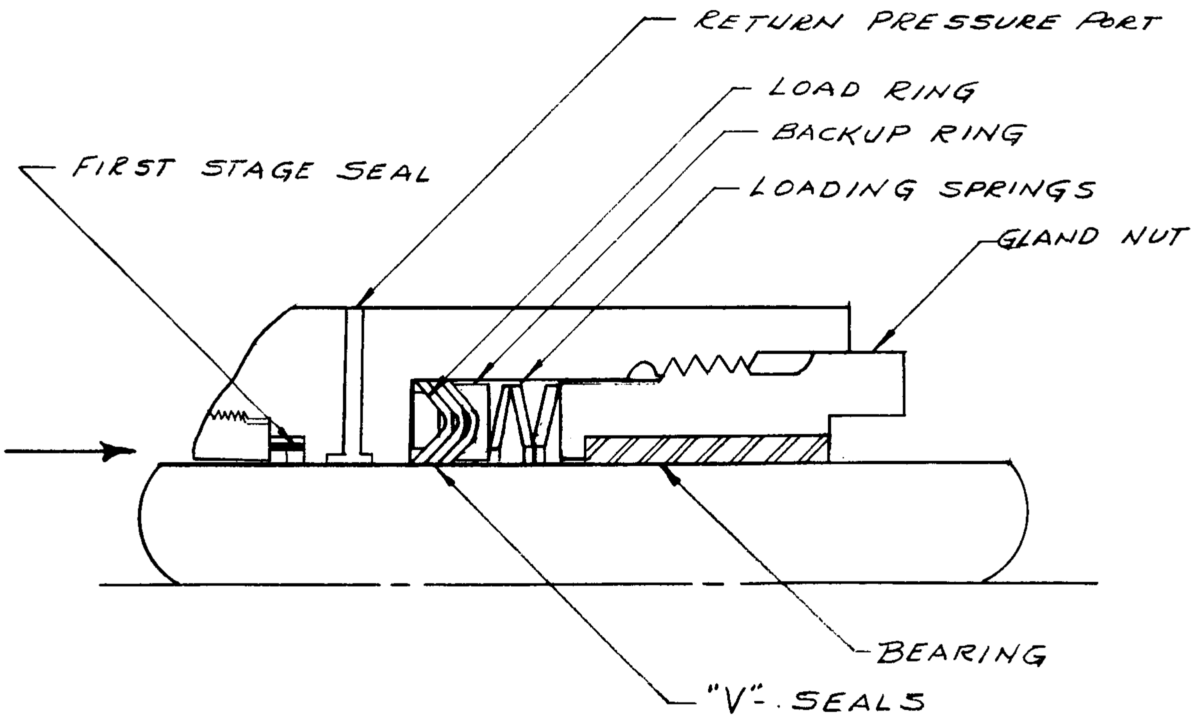

Figure 18. Polymer SP "V" Seal-Low Pressure

Figure 17 utilizes the relatively high elongation (approximately 3-4%) of the material to obtain a substantial interference fit over the shaft during initial assembly, and thus to induce the initial seal contact pressure without use of an external loading device. This contact pressure is further augmented by fluid pressure. Preliminary tests were conducted with this seal-material combination at 400°F, 500°F, and 600°F. Results show that zero leakage was maintained at temperatures up to 500°F. (See test section for detailed discussion.)

The V-seal design shown in Figure 18 has undergone substantial evaluation in previous seal programs conducted by the contractor (References 1 and 2). The seal consists of three sealing elements, a load ring, backup ring, and loading springs. The seal is assembled onto the shaft with essentially zero clearance. The outer leg provides the static seal and the inner leg effects a seal on the shaft. The springs are designed to give a constant load over a deflection of approximately 0.020-inch, which is considered adequate to compensate for wear. Experience (References 1 and 2) indicates that this configuration could also be adapted to a soft metal.

2. Seal Designs for Soft Metals

The soft-metal seal approach relies on the plastic deformation of the material to conform to the surface geometry of the piston rod. One of the primary considerations in this approach is to minimize welding of the seal material to the mating member. This is best met by metals of relatively low shear strength, such as silver. Spring mounting of this type seal would also be required to provide uniform loading of the seal to compensate for wear. The feasibility of this approach has been demonstrated (References 1 and 2) with the silver-base materials.

The seal design shown in Figure 19 consists of conical shaped sealing elements fabricated of a soft metal. The beveled edges of the inner and outer surfaces are used to effect sealing at the piston rod and seal gland, respectively. The loading rings are chamfered at an angle of 15 degrees so that, when they are tightened up, they tend to induce axial and radial motion of the seal. Static sealing at the gland face is accomplished by the beveled edge of the inner most ring. The small effective area of the seal that is exposed to the working pressure enables the use of a light loading spring. Therefore, contact stresses at the seal interface are kept to a minimum.

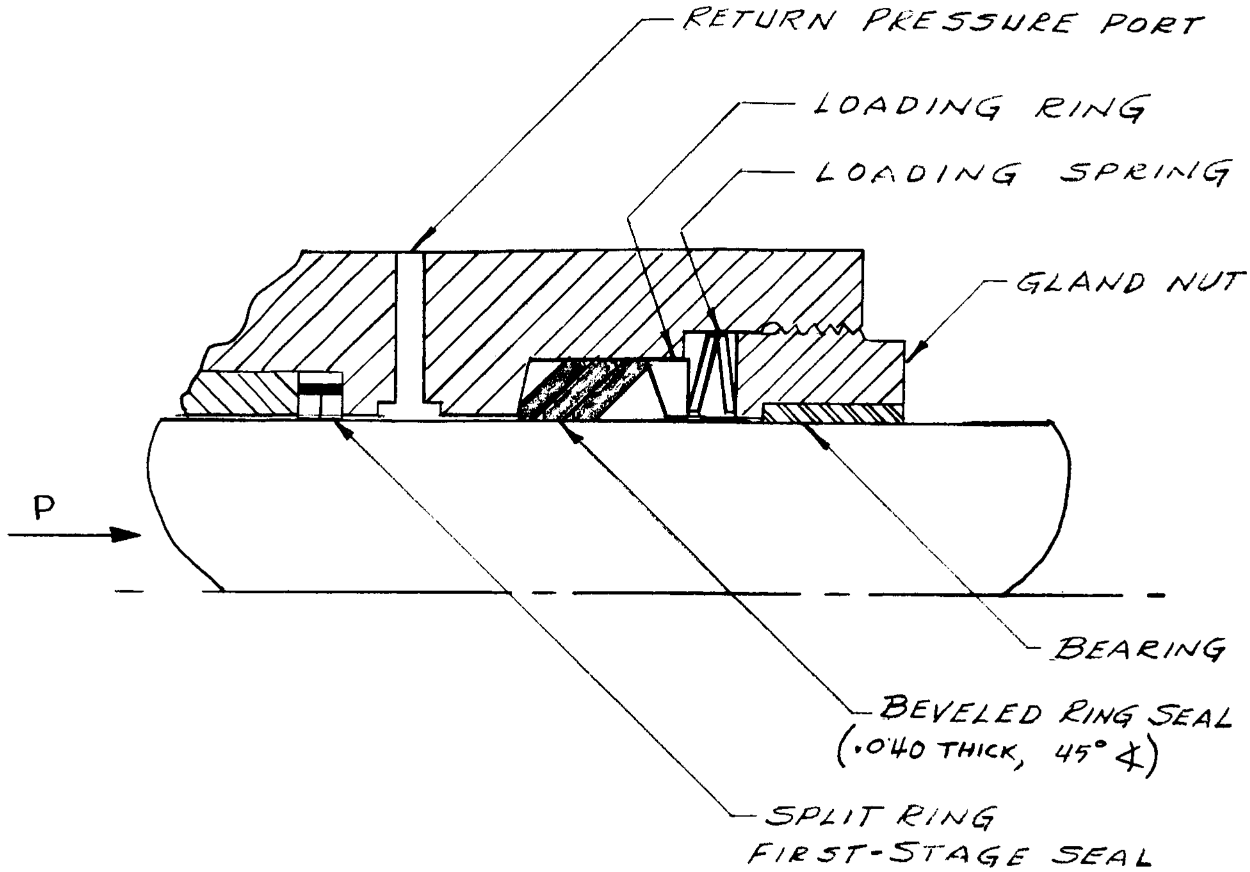

Figure 19. Bevelled Ring Seal (Soft Material)

3. Seal Designs for Hard Metal

The approach to a hard-metal seal is to design the seal to stretch elastically over the piston rod. The preload (hoop stress) induced will provide the contact pressure at the seal interface. However, the initial strain due to the preload must be within the elastic limits of the material. Since it is important that the material does not yield, the interference fit will be relatively small, and the material must possess good wear-resisting qualities in order to retain the induced load. Mechanical or pressure loading may be required to compensate for wear. Hard flame-plated coatings on the piston rod may be a requisite in obtaining good wear resistance.

The seal shown in Figure 20 is designed for use with hard metals or as a bimetallic seal (hard and soft metal combination). It consists of a series of sealing reeds approximately 0.005 to 0.007 inch thick that are stretched over the piston rod to obtain radial loading. The design of the seal permits the working fluid to provide additional loading. A mechanical spring deflects the sealing lips against the shaft in the event of loss or preload (interference) due to wear. The bimetallic version of this design, which appears to be the most promising approach, consists of alternate reeds of a hard metal and a soft metal. The hard metal provides the strength and the soft metal provides good conformability.

Figure 21 depicts a truncated-cone design that may lend itself to pressure balancing. Independent loading of the static and dynamic portions of the seal is accomplished by using separate adjusting nuts. Finer load adjustments are thus maintained. As shown in Figure 21, the sealing reed is preloaded against the rod by the initial interference fit. Based on stress calculations, using Vascojet-1000 (H-11 tool steel) as the seal material, an interference of approximately 0.004-inch can be achieved by working to a stress level of 135,000 psi (ultimate for Vascojet is 190,000 psi at 500°F). Analysis also shows that load relief at the seal interface by fluid pressure (100 psi) acting on the back of the reed is feasible. However, the radial deflection (0.00018-inch) of the seal is relatively small. The effects of this radial deflection can only be determined by actual test.

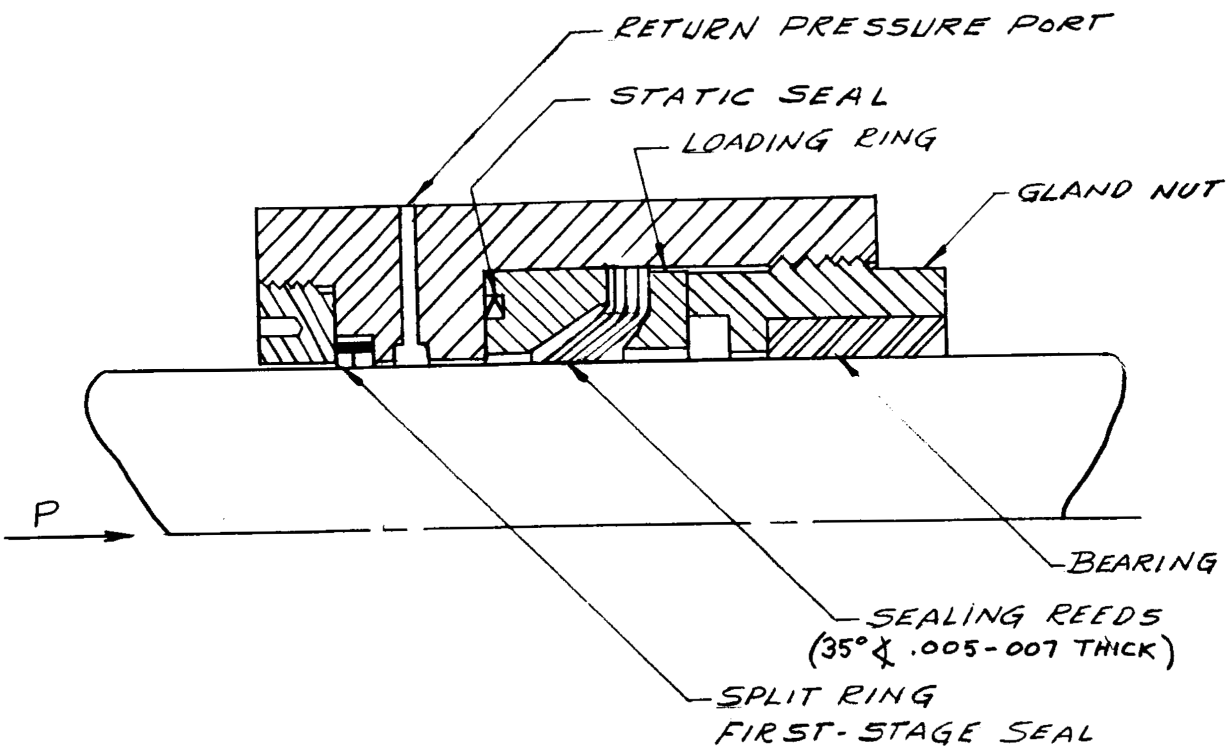

Figure 20. Metallic Reed Seal (Hand Metal)

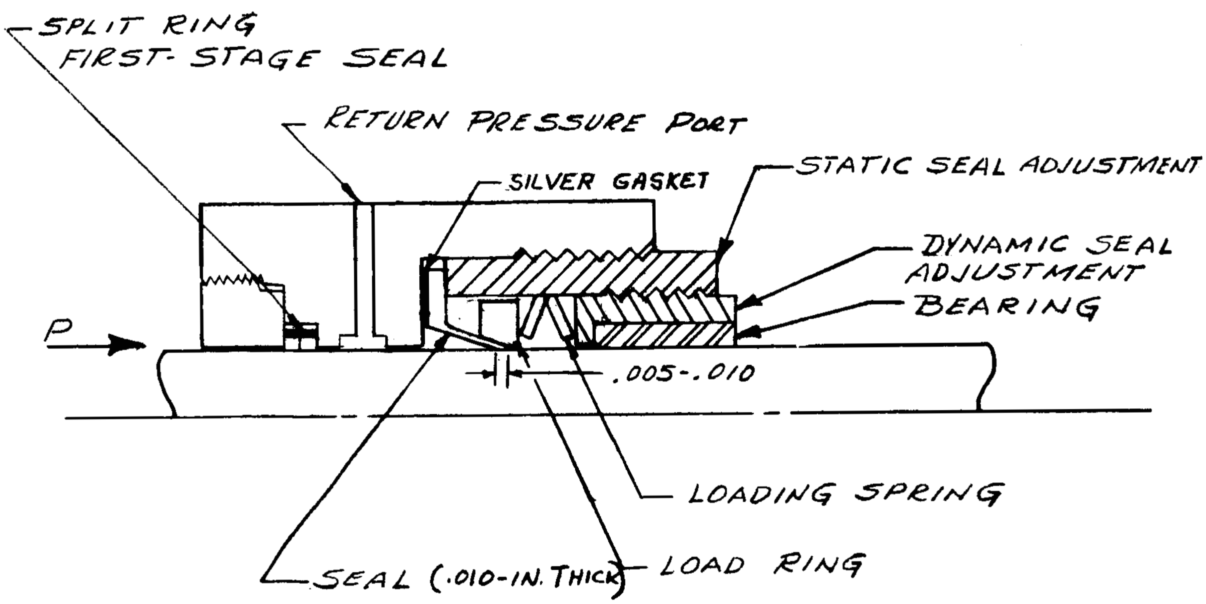

Figure 21. Metallic Lip Seal (Hand Metal)

C. COMMERCIAL SEAL DESIGNS

High temperature metallic seals under development by commercial concerns were surveyed for their applicability to the subject program. An all-metal seal submitted by B.F. Goodrich is being considered for evaluation in the subject program. The seal design proposed by B.F. Goodrich is a two-stage configuration. Basic design of the first-stage (high pressure) and second-stage (low-pressure) seal utilizes a knife edge or line contact method of sealing. However, only the low pressure seal has provisions for external adjustment to compensate for wear. Initial sealing is accomplished by an interference fit of approximately 0.0012 inch over the piston rod. Although Republic has emphasized the use of the chrome plating for the piston rod, BFG recommends that a flame-plated tungsten carbide (LW-1) coating be used in order to provide a hard bearing surface for the seal.

A design of a contracting two-piece split-ring rod seal assembly for high pressure applications was submitted by the Koppers Company. As shown in Figure 22, the seal consists of a Polymer SP sealing ring and a 17-4PH corrosion resistant steel spring. This type of seal provides good radial conformability. However, effective sealing in the axial direction requires continuous contact between the ring and the side of the groove. This requires close machining to obtain groove sides that are flat and free of waviness. Past experience with similar type seals (References 1 and 2) shows that leakage at 4000 psi and room temperature was between 26 and 30 drops per minute.

Wear life of the split-ring seal may be extended by employing hydraulic balancing to lower the unit loading on the ring.

D. PRELIMINARY EVALUATION

The "lip" seal (original design) shown in Figure 17, which consists of a truncated cone, was formed from a 0.030-inch thick polymer SP sheet. The rolled sheet is preferred over the billet form of the material because of its higher tensile properties and improved flexibility. The sealing element was formed with an included angle of 150 degrees. The inside diameter of the seal was machined smaller than the piston rod to allow for an initial interference fit of 0.020 inch. The hoop stress induced by the interference fit provided the seal

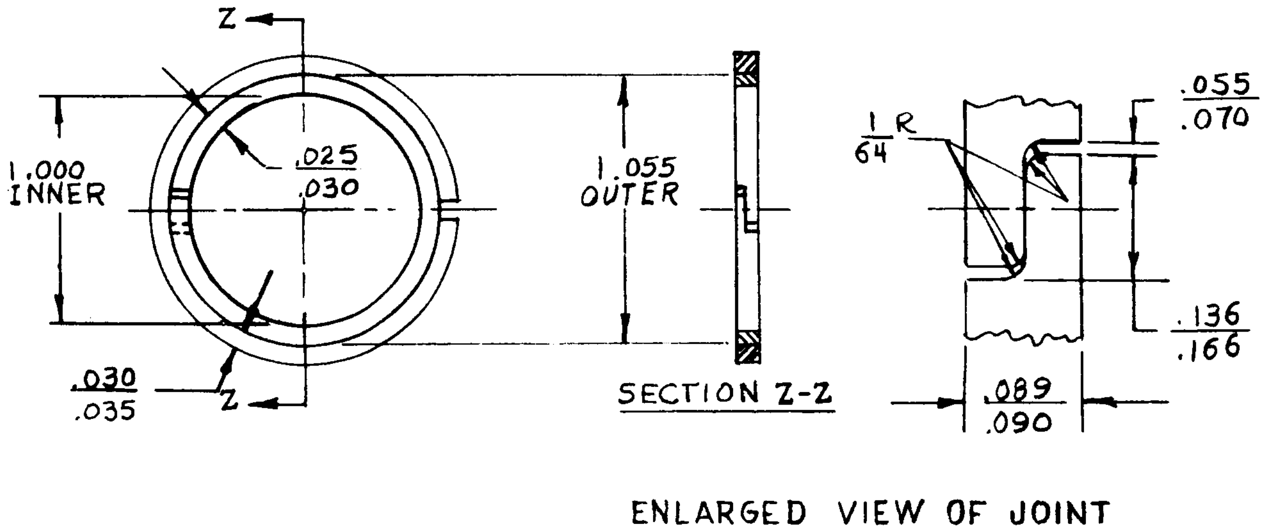

Figure 22. Contracting Two-Piece Split-Ring Seal

contact pressure for zero pressure sealing and to compensate for wear. During operation, the initial sealing force was augmented by fluid pressure acting on the sealing element.

Pressure checks were made with the seals assembled in the preliminary seal test unit shown in Figure 5. No leakage of fluid was observed at pressures up to 200 psi with F-50 silicone fluid. Further investigations were conducted to determine seal friction and thermal cycling effects on the seal.

The setup for determining seal breakaway friction, shown in Figure 23, consists of the seal tester and a driving cylinder. Seal breakaway friction is measured by pressurizing the driving cylinder, observing a dial indicator for initial motion and noting the pressure required to produce motion. Readings are taken at room temperature at 2-minute intervals. This pressure reading is converted to force based on the known areas of the piston of the driving cylinder less the friction of the O-rings in the cylinder.

Seal breakaway friction for pressures of 0 to 200 psi is shown below. As shown, friction for the Polymer SP lip seal is quite reasonable for a one-inch seal.

Fluid Pressure (psi)	Avg. Seal Friction (lb) (total for both seals)
0	131
50	133
100	136
150	146
200	147

Following the friction test, the seals were subjected to heat aging at 600°F to determine stress relaxation of the material. Each aging cycle consisted of heating from room temperature to 600°F, maintaining this temperature for two hours, then cooling to room temperature. After each aging cycle, seal breakaway friction was measured and the seal was disassembled and measured.

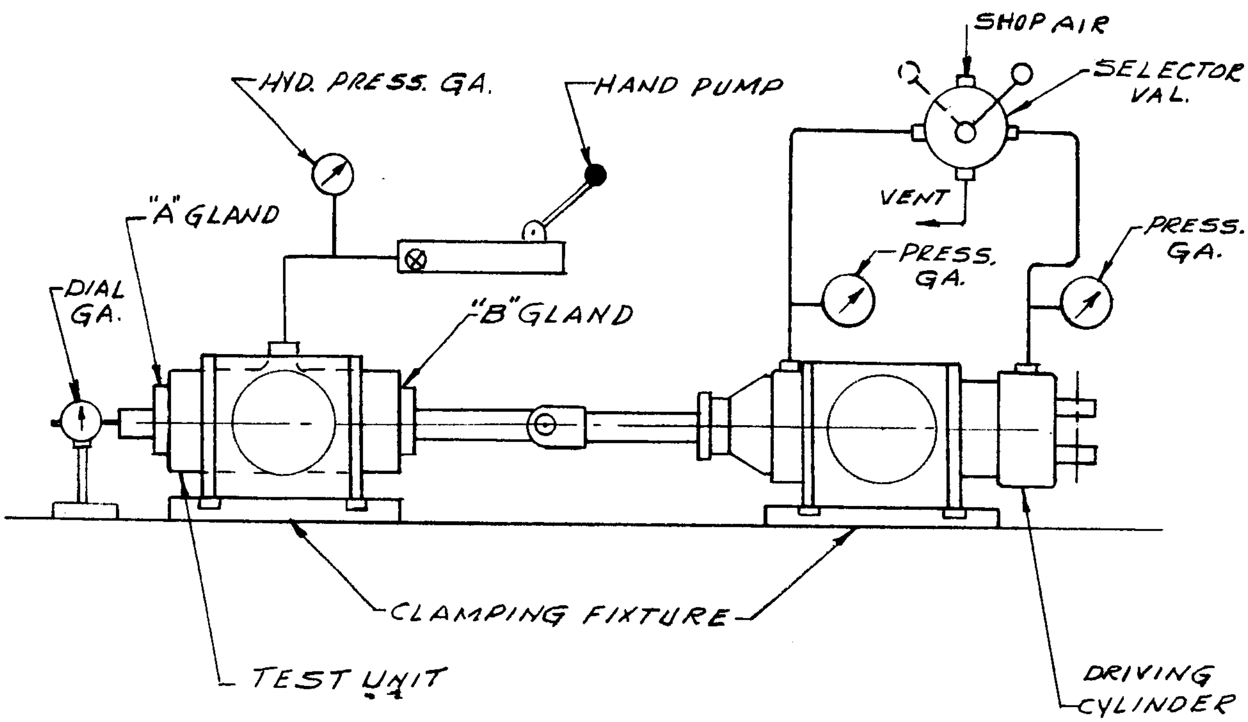

Figure 23. Seal Friction Setup

Seal friction and dimensional changes obtained after four aging cycles are presented below.

Aging Cycle	Seal Friction (0 psi)	Seal I.D. A-Seal	Seal I.D. B-Seal	Seal Interference A-Seal	Seal Interference B-Seal
Before Aging	131	0.9785	0.9775	0.020	0.021
1	82.5	0.990	0.990	0.0085	0.0085
2	82.0	0.990	0.990	0.0085	0.0085
3	82.0	0.992	0.993	0.0065	0.0065
4	81	0.9925	0.9935	0.006	0.005

These results indicated a substantial reduction in seal interference after eight hours at 600°F. As a result, friction was also lower. Final interference was approximately 30% and 23% of the original values for the A-seal and B-seal, respectively.

On the basis of the foregoing results, a second set of seals was fabricated and subjected to a cycling test to determine its wear characteristics. In this test, the seals were subjected to approximately 15 hours of cycling; 5 hours each at 400°F, 500°F, and 600°F. The piston rod stroke was 2-inches and was reciprocated at a rate of 30 cpm. Friction was measured after completing operation at each temperature plateau.

The seals completed the 400°F and 500°F cycling with no leakage. However, at the completion of the 600°F operation, leakage of approximately 5 drops per minute occurred on the B-seal. This leakage was caused by the seal gland nut backing off, resulting in excessive axial clearance in the assembly. This enabled the seal to move axially during cycling, which caused it to crack in several places. Evidence of permanent deformation of the seal was noticed, which indicated excessive deflection at the unsupported area.

Approximately 39% interference was retained on the A-seal. The B-seal showed a retention of about 11% to 20%, the lower values being attributable to the cracks in the seal, which relieved much of the hoop tension. The decrease in interference was indicated by the reduction in seal friction (Figure 24) recorded after operation at each temperature level. However, it is also possible that the lower friction was due to the burnishing of the piston with the Polymer SP seals during cycling. In general, the results obtained were very promising.

To further substantiate the Polymer SP lip seal as a candidate design, additional aging tests were conducted to determine stress relaxation characteristics during long-time exposure at 500°F and 600°F.

The aging test at 500°F was conducted with Polymer SP seals 0.030 and 0.060 inch thick. Each aging cycle consisted of heating from room temperature to 500°F, maintaining this temperature for 50 hours, and then cooling to room temperature. After each aging cycle, seal breakaway friction was determined and the seals were disassembled and measured. The results obtained after 350 hours of aging are presented below and in Figure 25.

As indicated in Figure 25, the 0.030-inch thick seal cracked after 150 hours at 500°F, resulting in the loss of 80% of its initial interference. Failure was caused by high stresses being concentrated at the outer periphery because of the method used in holding the seal in the cavity. Consequently, the seal was replaced with another 0.030-inch thick seal and testing continued. However, testing was monitored on the 0.060-inch thick seal only. A total of 350 hours was obtained with the latter with only a 43% loss in the initial interference.

Results of the Polymer SP aging test conducted at 600°F are shown below and in Figure 25. Relaxation of the seal material was quite pronounced at 600°F. As shown in Figure 25, a rapid drop occurred after 112 hours, representing a loss of approximately 88% and 92% for the A- and B-seal, respectively.

Aging Cycle	Hours at 600°F	Seal Friction (lb) at 0 psi	A-Seal I.D. (in.)	B Seal I.D. (in.)	Seal Interference (in.) "A"	"B"
Before Aging		105	.9841	.9789	.0144	.0196
1	50	56	.9920	.9935	.0065	.0050
2	112	37	.9973	.9961	.0012	.0024

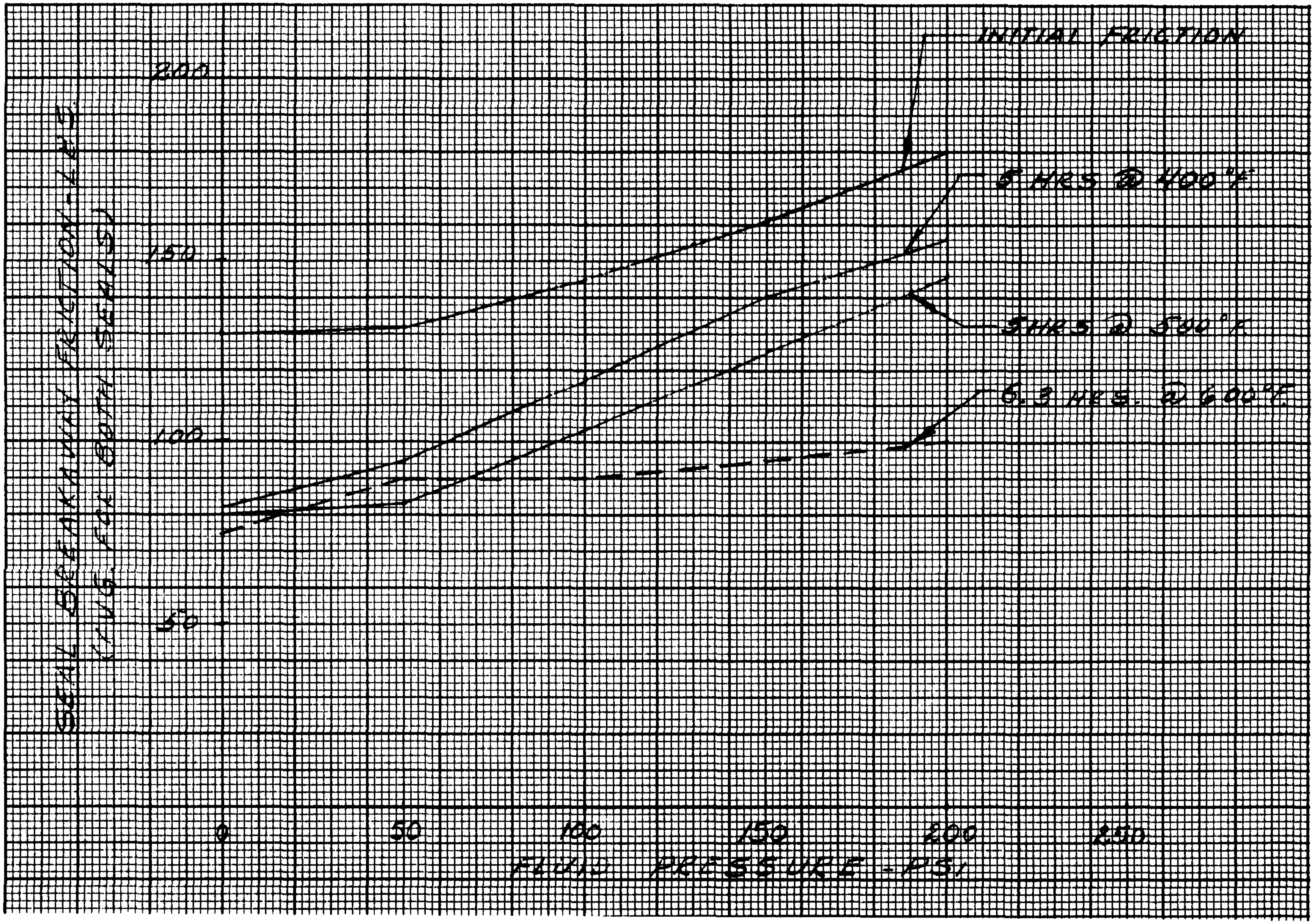

Figure 24. Seal Breakaway Friction vs Temperature Cycling

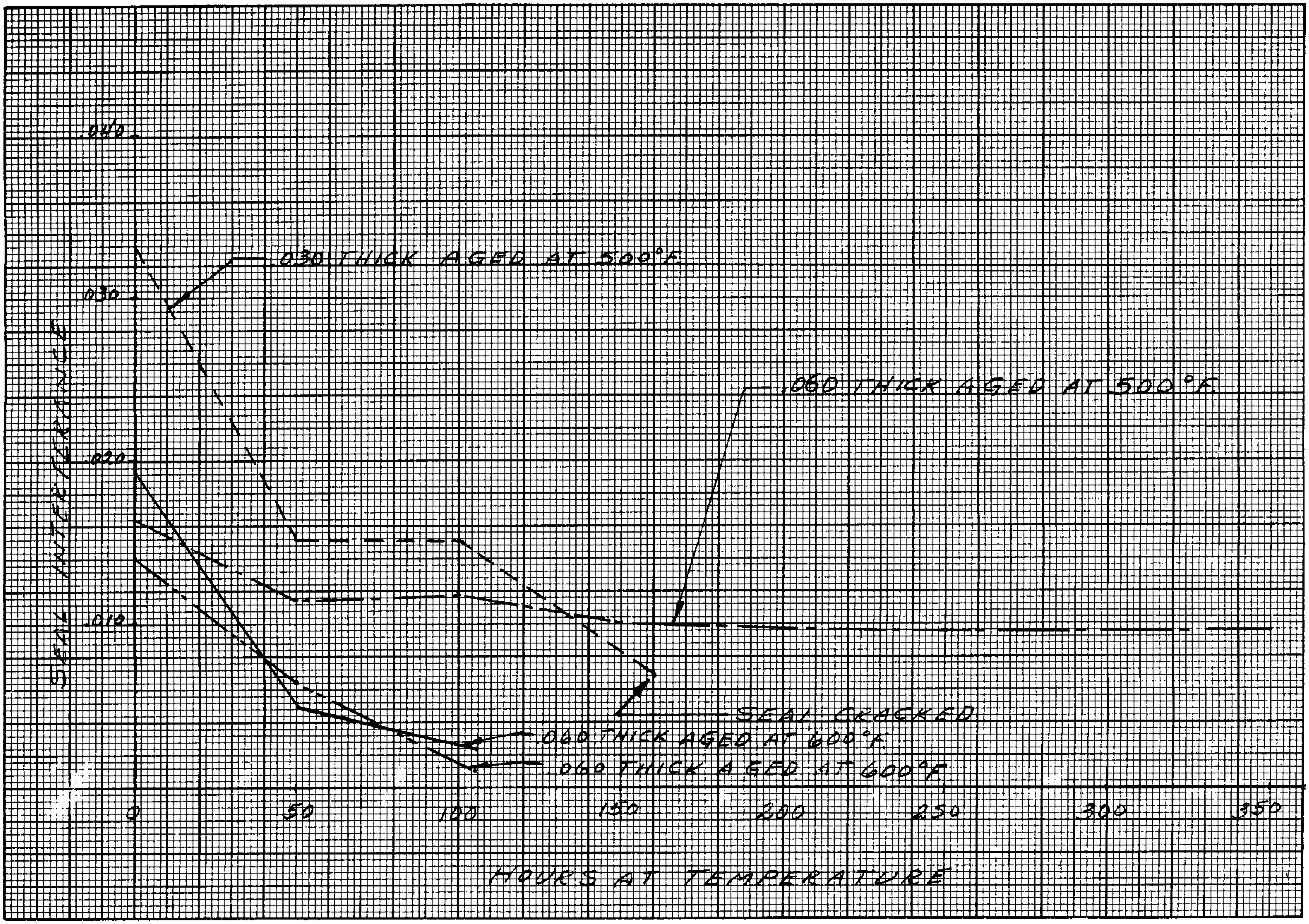

Figure 25. Polymer SP Aging Test

Since the lip seal design relies on the radial stresses induced at the inner diameter to effect a seal, the use of this seal at 600°F appears marginal with Polymer SP. However, at 500°F the material is able to retain a good portion of the hoop stress to maintain an effective seal. Based on the findings of these tests, certain modifications have been incorporated in the final seal design (see Figure 17). These include reduction of the clearance space between the seal and backup ring to limit seal deflection under pressure. The unsupported area of the seal is also reduced in order to keep stresses at the outer edges as low as possible.

FUTURE EFFORT

The schedule for the activities planned for the next six-month period is shown in Figure 26. The work to be accomplished consists of the following:

(1) Complete fabrication and assembly of the 1-inch and 3-inch seal test rigs.

(2) Set up hydraulic system for single-stage seal test.

(3) Conduct fluid compatibility and mechanical properties tests of candidate seal materials.

(4) Conduct wear compatibility of hard metal seal materials against chromium plating.

(5) Continue seal design work.

(6) Establish rating system for candidate seal designs.

(7) Select five candidate seal materials and best seal designs for low pressure testing.

(8) Conduct low pressure testing of 1-inch and 3-inch seals.

(9) Initiate design and test of high pressure single-stage seal.

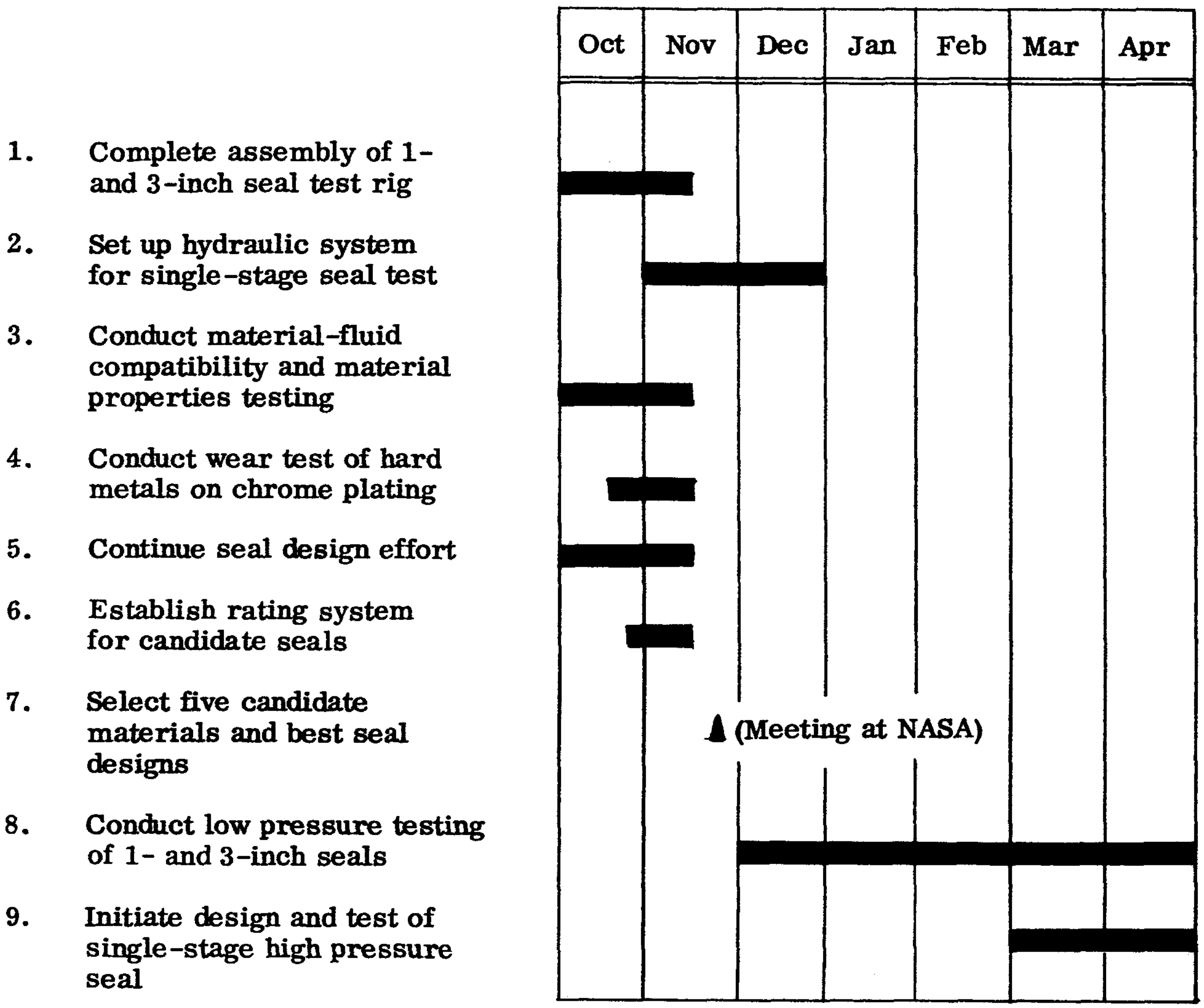

Figure 26. Schedule of Activities for Next Six-Month Period

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APPENDIX

EXHIBIT "A"

High Temperature Hydraulic System Actuator Seals

The Contractor shall furnish the necessary personnel, facilities, services and materials and otherwise do all things necessary for, or incident to, the work described below:

The work to be performed shall provide for the investigation of materials and designs of seals for potential use with hydraulic fluids in advanced supersonic aircraft. This investigation shall be directed to seals intended to function efficiently and reliably for 3000 hours in the temperature range -40°F to 600°F.

TASK I - Apparatus for Evaluation of Seal Materials and Designs

A. Facilities shall be provided for the measurement of hardness, elasticity, mechanical strength and other mechanical properties important to hydraulic system seals.

B. Facilities shall be provided in which seal materials can be evaluated at temperatures of 400°, 500°, and 600°F for chemical compatibility with five fluids to be selected by the Contractor with the approval of the NASA Project Manager. Periods of 150 hours shall be used. The fluids shall be degassed and compatibility shall be established in an inerted atmosphere system. Inerting shall be accomplished with 99.99 percent by volume nitrogen having an oxygen content of not more than 50 ppm, a hydrocarbon content (as methane) of not more than 50 ppm, and a dew point of -90°F or lower.

C. Facilities shall be provided for a rod seal test unit using one-inch diameter seals at 100 psi. Operation shall alternate between operation at 30-40 CPM with ± 2 to ± 4 inch stroke and 100-300 CPM with ± .05 to ± .10 inch stroke to simulate maneuvering and auto-pilot inputs to the actuator. The fluid temperature levels shall be 400°F, 500°F, and 600°F with the temperature for the seal in the actuator unit no less than the fluid temperature. Leakage and actuator forces shall be measured.

D. Facilities shall be provided for a rod seal test unit using seals of 1 inch and 3 inch diameters at pressures from 0 to 4000 psi. Operation shall include a cycling rate of 15-20 CPM with stroke length alternating from strokes (± ½ to ± 1 inch) to strokes (± 2 to ± 4 inch). Operation shall also include a cycling rate of 100-300 CPM with a constant stroke length (± .05 to ± .10 inch). The fluid temperature level shall be 500°F and the temperature of the seal in the actuator unit shall be no less than the fluid temperature. Leakage and actuator forces shall be measured.

E. Each component of the complete fluid systems test apparatus shall be identified by a code number which shall be scribed on the component. A complete log shall be maintained on each component to include the following: Manufacturer's designation and specifications; materials certification report; inspector's report; record of all tests (time and conditions): record of all post-test inspection reports, including photographs and failure analysis where applicable: record of all repairs and substitution of new components. These logs shall be updated at weekly intervals and maintained in a file which is available for inspection by the NASA Project Manager.

TASK II - Materials Selection, Procurement and Testing

A. The following classes of materials shall be considered for seals and/or gland bearing materials. Ten materials shall be selected by the Contractor with the approval of the NASA Project Manager. The selected materials shall be obtained and formed into appropriate test specimens for a one inch rod seal. In all cases, unless specifically approved by the NASA Project Manager polished hard chromium plating shall be used for the mating surfaces.

1. Polymide high temperature polymer (unfilled and metal filled)
2. Silver-metal composites developed by Illinois Institute of Technology under Air Force Contract No. AF33(616)-7310
3. Silver-polymer composite (Polymet)
4. Silver-base alloys or other soft phase duplex structures
5. Other metallic matrix materials
6. High strength metals (steel, titanium, cobalt, etc.)
7. New types of high temperature elastomeric materials
8. High temperature carbon graphite

B. Tests measuring bearing characteristics, hardness, elasticity, mechanical strength and other mechanical properties important to hydraulic system seals shall be made on the selected materials. All properties shall be determined at the projected maximum operating temperature, except hardness. Chemical compatibility tests with five fluids selected by the Contractor and approved by the NASA Project Manager shall be made at temperatures of 400°, 500° and 600°F. It is anticipated that these five fluids will be of the following types:

1. Chlorinated phenyl methyl silicone, General Electric Co. - F50
2. Super-refined mineral oils, MLO 60-294.

3. Monsanto Co. MCS 293 modified polyphenylether.

4. Monsanto Co. MCS 310 Halogenated polyaryl fluid.

5. DuPont fluid PR-143-AB, fluorocarbon.

Using the results of these tests the Contractor shall select five materials from the ten materials tested for further investigation under the following TASKS. The five materials selected shall be subject to the approval of the NASA Project Manager.

TASK III - Seal Design Development

A. Seals shall be designed which most effectively use the mechanical properties of the individual materials selected in TASK II for further investigation. Design studies shall provide for such consideration of the selected materials as to give optimum rod-end seal designs for each material. Such designs may logically provide for spring mounting to compensate for reduced elasticity, pressure balancing to improve endurance and the use of coatings or films as needed because of varied conformability. The seal designs shall be subject to the approval of the NASA Project Manager.

TASK IV - Low Pressure Tests

A. The five seal materials and designs shall be tested in the one-inch diameter 100 psi pressure rod and seal test facility described in TASK I. The best seal material and designs from one (1) inch diameter test shall be evaluated in three (3) inch diameter seals under otherwise identical conditions. The test fluid shall be chlorinated phenyl methyl silicone unless the NASA Project Manager directs that another fluid shall be used instead. Operation shall be for 50 hours (or until seal failure, if less than 50 hours) at each of the fluid temperature levels 400^o, 500^o, and 600^oF. Operation shall alternate between operation at 30-40 CPM with $\pm$ 2 to $\pm$ 4 inch stroke and operation at 100-300 CPM with $\pm$ .05 to $\pm$ .10 inch stroke. Seal leakage and actuator forces shall be measured. Seal leakage in excess of one drop per minute or a two-fold increase in required operating force shall be criteria for seal failure. These criteria may be modified with the approval of the NASA Project Manager.

TASK V - High Pressure Tests

A. Three materials selected by the Contractor from the results of the low pressure tests and approved by the NASA Project Manager shall be tested in the 0 to 4000 psi rod seal test unit described in TASK I. These tests shall run for a total of 3000 hours or until seal failure occurs. A single test apparatus capable of both the low pressure tests described in TASK IV and the high pressure tests to be described in this TASK V may be used. Rod end seals of 1 inch diameter and rod end seals of 3 inch diameter shall be tested concurrently in the same unit at a pressure of 3000 to 4000 psi with the following operational cycle:

1. Operation for 35 minutes at 15-20 CPM alternately using ± 1/2 to ± 1 inch stroke and ± 2 to ± 4 inch stroke. Fluid Temperature shall increase approximately linearly from 100°F to 500°F during this period. Ambient temperature shall be increased in a 150 minute period.

2. Operation for 125 minutes at 100-300 CPM using ± .05 to ± .10 inch stroke. Fluid temperature shall be at 500°F.

3. Operation for 20 minutes at 15-20 CPM alternately using ± 1/2 to ± 1 inch stroke and ± 2 to ± 4 inch stroke. Fluid temperature shall decrease approximately linearly from 500°F to 100°F during this period.

B. In addition, a single-stage high pressure one (1) inch diameter seal, fabricated from the best material under Para. "A", TASK V, shall be developed and evaluated in the endurance rig described in TASK I, at:

1. Temperature, 500°F.

2. Pressure, 300 psi, maximum.

3. Test profile described in TASK V, Para. A.

4. The seal shall be designed and tested to failure or 100 hours with subsequent redesign and testing subject to approval of the NASA Project Manager.

C. For all operations seal temperatures shall be no less than the fluid temperatures. Following every 20 such cycles the seal assembly shall be subjected to a 4 hour cold-soak at -40°F ambient. The leakage in the cold system shall be checked at the end of the soak period and continuously during warm-up prior to the subsequent operational cycle.

D. The operational cycle described above shall be considered typical of test requirements but shall be subject to redirection by the NASA Project Manager. The test fluid shall be chlorinated phenyl methyl silicone unless the NASA Project Manager directs that another fluid shall be used instead.

E. Seal failure criteria sufficient for the termination of a run are leakage in excess of one drop per minute or a two-fold increase in operating force.

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